

DESCRIPTION AND DESIGN OF LIQUID-METAL  
RADIATOR AND CONDENSER TEST FACILITY

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# DESCRIPTION AND DESIGN OF LIQUID-METAL

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Lewis Research Center

### SUMMARY

Investigation of the performance and problem areas of heat-rejection systems for space turboelectric power generating systems requires a suitable facility capable of test operations with liquid metals and reasonable components sizes. Such a facility has been in operation at the NASA Lewis Research Center for research on multitube liquid-metal space radiators and condensers. This facility was designed for potassium vapor generation at temperatures up to 1800<sup>0</sup> F, with a heat-rejection rate of 150 kilowatts. A capability was provided for testing multitube NaK-cooled condensers, radiation-cooled vapor radiators (direct condensing), or radiation-cooled liquid-flow radiators (indirect condensing). Radiation cooling was obtained with a large (8 by 18 ft) oil-cooled vacuum chamber. The principal test components (boiler, condenser, and radiator) were horizontally-oriented to minimize the effects of gravity.

A discussion of the principal design features of the liquid-metal radiators and condenser test facility is presented. An overall description of the facility is given, including cycle considerations, general facility specifications and layout, and descriptions of the heating, vapor, and cooling loops. This description is followed by a presentation of detailed design considerations and descriptions of the various components. Included are loop piping, oxide control and indicating systems, vacuum chamber, loop pressurization and vacuum-pumping systems, and instrumentation. The detailed design specifications submitted for the construction of the facility are also included.

### INTRODUCTION

Large amounts of electrical power will ultimately be needed in outer space to supply the requirements of communication and other satellites, manned space laboratories,



lunar-based operations, and electrically propelled spacecraft. Many energy-conversion cycles that convert solar heat or nuclear reactor heat to useful electrical output have been proposed for these applications. The principal contenders include the Rankine cycle turbogenerator using a liquid metal, the Brayton cycle turbogenerator using an inert gas, and the thermionic emitter.

All closed thermal energy-conversion cycles for use in space have one process in common: waste heat must be dissipated to the surrounding space by thermal radiation. Consequently, every space power-generating plant will incorporate a radiating-type heat-rejection system. Preliminary studies have indicated that the heat-rejection system will be the largest component of the powerplant, possibly 20 to 40 percent by weight depending on cycle conditions, construction, and meteoroid protection desired. Since weight economy and reliability are principal factors in all spacecraft design, research on radiator and condenser components is most important in the proper development of heat-rejection systems.

This report presents a description and design details of a ground-based liquid-metal research facility to conduct applied research on the heat-rejection systems of space powerplants using the Rankine vapor cycle. The facility can be used to determine the characteristics and performance levels of various prototype heat-rejection components and to investigate component interactions and system operating characteristics. The report contains the cycle considerations, general specifications, and general layout for the facility; description and details of the individual components of the facility; and the original specific design and construction specifications (see appendix) for the entire facility.

The facility was designed and fabricated for the NASA Lewis Research Center by the Pratt and Whitney Company, Connecticut Advanced Nuclear Engine Laboratory (CANEL), Middletown, Connecticut. The contract for construction (NAS 3-1833) was awarded on July 1, 1961. On July 1, 1962, the major components were delivered to the Lewis Research Center for installation by the Center. A year later, NASA completed the installation of the facility and started to checkout its operation. The first research data runs were completed on a multitube condenser model in January 1964.

## FACILITY DESCRIPTION

The purpose of the facility was to conduct applied research on prototype heat-rejection systems and their components for Rankine cycle electric powerplants for space use. Specifically, the facility would be utilized to conduct investigations of the performance levels and operating problems of promising system components, to obtain experience in the design and operation of liquid-metal loops, and to establish techniques and relations for the design of such system components for eventual application to space. To

best meet these objectives, it was necessary that the facility be patterned after advanced Rankine cycle powerplant designs, and be sufficiently flexible and versatile to accommodate and test a wide variety of concepts and configurations.

## Cycle Considerations

Schematic diagrams of the basic elements of the Rankine cycle concept for space-power use with two arrangements for the radiative heat rejection are shown in figure 1. These powerplants operate in the following basic manner. A circulating fluid in the reactor loop picks up heat generated in the nuclear reactor, then flows to the boiler where it transfers its heat to the working fluid, vaporizing it. (A separate fluid is presumed here because the direct boiling of fluids inside a reactor was not considered feasible at the time the facility was designed.) The vaporized working fluid, which may be different from the reactor coolant fluid, is expanded through a turbine, with a drop in pressure and temperature, to drive a generator that produces the desired electrical output.

The turbine exhaust vapor must be condensed completely and the liquid then pumped back into the boiler. The boiler vaporizes this liquid at nearly constant pressure to complete the cycle. The heat given off by the turbine exhaust vapor, when it is recondensed and subcooled to some extent, constitutes the cycle waste heat that must be dissipated to surrounding space by the heat-rejection system.

The difference in the two systems (fig. 1) is the method of transporting this waste heat to the heat-dissipating radiator. In the direct-condensing system (fig. 1(a)), the turbine exhaust vapor flows directly to the radiator where it condenses on the inner surfaces of the radiator, while the heat of condensation (and the heat of subcooling) is radiated from the outer surfaces of the radiator; the condensate is then pumped from the radiator back to the boiler. This arrangement is referred to as a two-loop or direct-condensing system. Since the radiator involves two-phase condensing flow, it operates at essentially constant temperature. Also, the pressure drop in the radiator constitutes a pressure drop for the cycle.

In the indirect-condensing system (fig. 1(b)), the turbine exhaust vapor flows to a convective heat exchanger where the heats of condensation and condensate-subcooling are transferred to a coolant liquid. This liquid flows to the radiator where it gives up its heat by radiation and undergoes a temperature drop; then it is pumped back to the condenser to absorb more heat. For a given heat load, the design liquid flow rate varies inversely with the overall temperature drop. The coolant liquid pressure drops across the radiator and condenser are made up by the circulating pump.

The additional loop of the indirect-condensing arrangement adds greater flexibility to the heat-rejection system for the following reasons: (1) the temperature drop of the

all-liquid radiator can be varied for a given design heat load, (2) a coolant fluid different from the vapor-loop working fluid can be used (e. g. , to ease the startup and freezing problem or to obtain best overall fluid properties), and (3) cooling can be obtained with cocurrent, countercurrent, or combinations of coolant flow paths for the condenser. Furthermore, the indirect system with heat-exchanger condensers can provide effectively for redundancy because, if any one of several independent radiator loops are made inoperative due to meteoroid damage, no catastrophic loss of vapor-loop working fluid will result. The three-loop system can also be used in conjunction with a compact jet or contact condenser in which vapor condensation is obtained from direct mixing with the coolant liquid from the radiator. In this case, however, identical working and coolant fluids would have to be used.

The comparative disadvantages of the three-loop system are a generally heavier radiator weight and an additional weight and power drain associated with the circulating pump system and its controls. Comparison of the two systems is a complex evaluation based on many considerations such as system weight, complexity, materials selection, structure, startup, partial-load operation, ground testing, and vehicle integration. It is important, therefore, that a facility designed to investigate heat-rejection systems be capable of accommodating a variety of component configurations.

## Facility Specifications and Layout

In consideration of the previous discussion and other factors, the following major specifications were adopted for the facility design:

- (1) Provide flexibility for investigating both direct- and indirect-condensing systems
- (2) Provide vapor at the inlet to the condensing components at conditions typical of the turbine exhaust
- (3) Provide for reasonable test component sizes compatible with scaling, cost, fabrication, and instrumentation requirements
- (4) Maintain orientation of the principal vapor-loop components so that the effects of gravity on two-phase flow will be minimized
- (5) Permit installation of a powered turbine or turbine simulator to provide for complete power-loop operation
- (6) Operate at temperature levels consistent with powerplants of interest without resorting to refractory materials

On the basis of these general specifications, a three-loop facility employing an electric heater and a vacuum chamber was decided upon (see the basic process flow diagram shown in fig. 2). The facility is composed of an oil-cooled-wall vacuum chamber for housing the radiators and absorbing their heat and three closed-return alkali-metal fluid loops (a heater loop, a vapor test loop, and a cooler loop). Each loop is equipped with a

fluid purification system, an inert-gas blanket system, sump or fluid storage tanks, and expansion tanks. The condensing and boiling circuit is constructed in a horizontal attitude; that is, all the components and interconnecting piping lie in a common horizontal plane in such an attitude that vertical gravity-induced density stratification is limited to one diameter of the pipe carrying the fluid. Also, driving and retarding forces due to gravity weight will thus be minimized. It was felt that by restricting the attitude of the circuit to a common horizontal plane some of the dynamic problems of weightlessness in outer space operation may be simulated. Figure 3 gives an isometric drawing and an overall view of the facility showing the location and orientation of the major components.

Potassium was selected for the working fluid in the vapor loop on the basis of vapor pressure level and applicability to systems having development potential. The facility power level was sized to reject 150 kilowatts (510 000 Btu/hr) of heat in the test sections. For typical Rankine cycles of interest, this heat-rejection rate corresponds to about 25 kilowatts of useful power delivered by the turbine at an inlet temperature of  $1800^{\circ}\text{F}$  (with  $75^{\circ}\text{F}$  of superheat). For potassium, at this temperature level, the turbine exhaust may vary from  $1300^{\circ}$  to  $1600^{\circ}\text{F}$  in temperature, 8 to 45 pounds per square inch absolute in pressure, and 75 to 100 percent in vapor fraction. These operating ranges and the turbine inlet condition established the thermodynamic design criteria for the facility and its components.

The facility was required to perform for a period of 10 000 hours of Rankine cycle operation. Each test was anticipated to require approximately 200 hours. During 75 percent of the 10 000 hours, the facility was to operate without a turbine with a maximum boiling fluid temperature of  $1600^{\circ}\text{F}$ . During the remaining time, with a turbine, the maximum temperatures of the heating circuit, the boiler, and the superheater were not to exceed  $1800^{\circ}\text{F}$ .

Nonturbine operation of the facility for the individual component research requirements and configurations that the facility can accommodate are illustrated in figure 4; only that part of the facility in use is connected by solid lines in each view. Facility design conditions are given for each operating mode; in all cases shown, the heating circuit remains unchanged. For tests of a direct-condensing radiator (fig. 4(a)) the valves downstream of the superheater are operated to direct vapor into the test radiator located in the vacuum chamber. The heat given off by the radiator is absorbed by the oil coolant in the chamber wall, and the radiator condensate is returned to the test-loop pump for recirculation. Typical operating conditions with  $200^{\circ}\text{F}$  subcooling and with no parasitic heat losses are indicated in the figure.

The flow diagram for test operation of a heat-exchanger condenser is shown in figure 4(b). In this mode of operation, the vapor flow is directed into the test condenser located within the facility enclosure (see fig. 3(a)). The test condenser is cooled by a liquid NaK coolant, which is shunted through the main air cooler in the enclosure. A

wide range of coolant flow rate and temperature drop can be obtained through control of the NaK circulating pump and the air flow through the main air cooler. Complete condenser performance maps can thus be obtained. Operation with a 100° F rise in coolant temperature across the condenser, which was the specified minimum at maximum load, is indicated in the figure.

In the arrangement indicated in figure 4(c) for operation of a heat-exchanger condenser cooled by a radiator, vapor is directed into the condenser within the loop enclosure as in the previous case; however, the NaK coolant now bypasses the air cooler and is directed into a liquid-phase-type flow radiator in the vacuum chamber for cooling. Conditions shown in the figure are for a 100° F temperature rise in the condenser. For this coupled mode of operation, allowable variations of coolant flow rate for a given condenser temperature and heat load will be substantially reduced for a given radiator because of its fixed area.

A photograph of the facility loop enclosures and vacuum chamber is shown in figure 3(b). Elements of the heating and vapor loops are seen through the open doors of the enclosure. The large pipe in front of the enclosure is the air-cooling exhaust line. A view of the enclosure for the test condenser model is shown in figure 5.

## Loop Descriptions

Heater loop. - This loop (fig. 2) simulates the power system reactor loop which provides the heat source and supplies hot liquid metal (NaK) to the potassium boiler at temperatures up to 1800° F. The NaK is pumped by an electromagnetic pump to the main heater where it is heated by means of its electrical resistance to an impressed current. The hot NaK then leaves the heater, enters the boiler, and gives up heat to vaporize the potassium flowing inside the boiler tubes; the cooled NaK then returns to the pump for recirculation.

An oxide control and indicating system is located in an auxiliary circuit around the pump. This system includes a hot trap for chemically removing oxygen, a cold trap for physically removing oxides, and a plugging indicator for measuring the oxide concentration in the NaK.

The liquid NaK is stored in a sump tank when the facility is inoperative. This tank was made sufficiently large to contain approximately twice the volume of liquid contained in the loop. Thus a quantity of cold liquid metal is maintained in the sump tank to cool the incoming hot liquid introduced during the loop-emptying process. The possibility of a tank rupture caused by thermal stresses from a sudden large temperature rise can thus be avoided. Valves are closed to isolate the sump tank from the loop during operation.

A pipe branch that leads to an expansion tank is located at the point of highest eleva-

tion in the loop upstream from the inlet to the boiler. This tank allows room for expansion of heated liquid metal and also serves as a pressurizing chamber for establishing the operating pressure of the heater loop.

The maximum design operating pressures and temperatures at various heater loop stations are indicated in figure 2. The pressures shown are sufficiently high to suppress boiling of the hot NaK with enough margin remaining to overcome velocity head pressure drop as well as friction losses in the pipe. The maximum flow of 31 000 pounds per hour (105 gal/min) at 1800° F was established to limit the maximum temperature change in the loop to 75° F at maximum heat load. Larger temperature increments would increase the mass transfer rate of nickel from the loop piping and thereby tend to reduce the active life of the loop.

Vapor loop. - The vapor (test) loop (fig. 2), which circulates the potassium working fluid of the conversion cycle, consists of five major components through which the main stream flows: (1) the boiler, (2) superheater, (3) research (test) condenser, (4) subcooler, and (5) pump. The minor components are: (1) the sump and expansion tanks, (2) the hot trap, and (3) the liquid sample removal station. As shown in figure 2, liquid potassium is pumped by an electromagnetic pump into the boiler tubes where it is vaporized by the hot NaK from the heater loop. The vapor leaves the boiler and enters the superheater where its temperature is further increased by electric radiant heaters. The vapor then flows to a T-connection through a hand-operated valve located in each leg where it may then be diverted either to the vacuum chamber that houses a radiative condenser or to a convective condenser that is cooled by the NaK circulating in the cooler loop. A photograph of the enclosure containing the convective condenser loop is shown in figure 5. The condensate from either condenser flows through hand-operated isolating valves into a common line that connects to the inlet of the electromagnetic pump through a subcooler. The subcooler is used to ensure that no vapor enters the pump.

The maximum operating temperature of the vapor can be at one of two levels dependent on whether or not the loop contains a turbine. When a turbine is used, the boiler will deliver saturated vapor at 1725° F. The superheater then adds 75° F of superheat; thus, superheated vapor at 1800° F will be available at the entrance to the turbine. If a turbine is not used, the vapor will then be delivered to the condensers to simulate the turbine discharge. In this case, the boiler needs to deliver vapor heated to only 1600° F. The superheater operation can then be optional as a fine adjustment for the vapor quality.

In order to minimize piping erosion within the loop, the maximum allowable design vapor velocity was established at 200 feet per second and the maximum liquid velocity at 15 feet per second.

Both the sump and expansion tanks connect to the mainstream at a common point upstream of the subcooler; the expansion tank is located above the loop while the sump is below. Consequently, the sump tank contains a submerged tube (deep tube) for discharg-

ing the liquid upward from the tank. Each tank can be isolated from the loop by its own remotely operated valve. The expansion tank valve is equipped with a valve positioner to hold it at any intermediate opening between full open and full closed.

Both the hot-trap loop and the sample-station loop are bypasses around the pump and subcooler. The flow through the hot trap is controlled by a throttling valve, while the flow through the sample station is controlled by an on-off isolating valve. All metal surfaces of the loop that are in contact with potassium are preheated by electric strip heaters to a temperature well above the potassium melting point ( $145^{\circ}\text{ F}$ ).

Cooler loop. - The cooler loop contains the heat-transfer fluid for removing the heats of condensation and subcooling released in the test condenser in the vapor loop. The cooler loop was designed to permit operation with either NaK, sodium, or potassium. Since the alkali-metal coolants are always circulated in a liquid state, the loop operation, inventory, and pressure controls are identical to the heater loop. The primary components and their interconnections are shown in figure 2. After the fluid has been heated in the potassium condenser, it flows to a pair of hand-operated valves. These valves may be set to direct flow either to the vacuum chamber, which would contain a liquid-flow radiator, or to an air-cooled heat exchanger. The cooled liquid is then returned to the condenser by an electromagnetic pump.

The maximum operating temperature of the cooler-loop flow cannot exceed the temperature ( $1600^{\circ}\text{ F}$ ) of the potassium vapor entering the condenser from the test loop. The temperature rise of the coolant during the condensing process depends on the flow rate of the coolant. In powerplant design, the desired flow rate value (or temperature rise) is a matter of design tradeoffs: a maximum design flow of 105 gallons per minute was selected as a representative value for use in this loop. The smallest temperature rise without subcooling at rated power (150 kW) would then be  $75^{\circ}\text{ F}$  ( $100^{\circ}\text{ F}$  with subcooling). Provision was made for preheating the entire loop in order to allow the use of potassium or sodium as the heat-transfer fluid. The cooling air for the air-cooled heat exchanger was supplied by an existing exhaust fan at the facility site, which could supply 10 000 pounds of air per hour at  $100^{\circ}\text{ F}$ .

## COMPONENT DETAILS

### Piping

Material selection. - All the components that are in contact with alkali metal were fabricated from pipe, tubing, plate, or bar stock; no castings, special forgings, or formed sheets were used. The pipe and tubing were extruded with seamless walls, with the exception of the 4-inch-diameter cylinders used for the boiler shell and the hot-trap body in the heating loop.

The design operating temperature ranges of the facility components required the use of two nonrefractory materials: an iron-base alloy (type 316 stainless steel) for the zones operating up to 1600<sup>0</sup> F and a cobalt-base alloy (HS-25) for the zones operating above 1600<sup>0</sup> F. Type 316 stainless steel was preferred over other 300-series stainless steel because it exhibited more strength at temperatures over 1200<sup>0</sup> F, was considered more resistant to corrosion by alkali metals, and presented fewer fabrication problems. The chemical compositions for both the stainless steel and HS-25 are given in table I. These values were taken from sample certified compositions provided by the supplier.

Stress calculations. - The limiting stress levels in the facility piping were defined by the creep rupture obtained after 10 000 hours, the useful life specified for the temperature involved. Two typical stress-to-rupture values at 10 000 hours for type 316 stainless steel are 4160 pounds per square inch at 1400<sup>0</sup> F and 1330 pounds per square inch at 1600<sup>0</sup> F. Stress-to-rupture values for HS-25 up to 10 000 hours were not available; however, available manufacturer's data up to 1000 hours were extrapolated and used (table II).

The allowable working stress was taken as one-third of the stress to rupture modified by a weld efficiency of 60 percent. The following formula was used:

$$\sigma_A = \frac{\sigma_R}{3 \left( 1 + \frac{E}{100} \right)} \quad (1)$$

where

$\sigma_A$  allowable working stress, psi

$\sigma_R$  stress to rupture, psi

E welding efficiency, percent

A summary of all the calculated stresses in the facility piping is given in table III along with the safety factors. An examination of the tabulated stresses showed that at design temperature all components had reasonable safety factors. A calculation for the heater tube at 1900<sup>0</sup> F indicated that it could become the most critical element in the event of an overtemperature excursion because of the low safety factor.

All the critical piping was examined for thermal expansion stresses. The pipes were analyzed as straight segments acting as guided cantilever beams perpendicular to the expansion that each segment was expected to absorb. It was assumed that all expansions were absorbed by direct bending of the segments and that all pipe bends were sharp corners. The strains were calculated from the following equation:



$$e = \frac{3yd}{L^2} \quad (2)$$

where

- e elastic strain, in./in.
- y expansion to be absorbed, in.
- d outer diameter of pipe segment, in.
- L length of pipe segment, in.

The maximum allowable strain at any temperature was chosen as 0.003 inch per inch. All critical piping was found to be within allowable strain limits although some marginal sections required stops and special anchors to prevent overstrain. One example is the rolling support used for the heating-loop pump piping (fig. 6).

Pressure losses. - The hydraulic pressure losses of the alkali-metal flows were calculated in all the sections of the piping systems. For the friction loss calculation, the alkali metal flowing in any one pipe section was considered to be isothermal and in either one of two incompressible states: all liquid or all vapor. The specific volume of the vapor was evaluated at its average pressure since the pressure losses were expected to be small.

The liquid pressure loss for any segment of pipe is given by the following equation (ref. 1):

$$\Delta P_L = 8.64 \frac{\rho Q^2 L \psi}{d^5} \times 10^{-4} \quad (3)$$

where

- $\Delta P_L$  liquid pressure loss, psi
- $\rho$  liquid density, lb/ft<sup>3</sup>
- Q liquid volume flow, gal/min
- L length of pipe segment, ft
- $\psi$  dimensionless correction factor for wall roughness, viscosity, etc.
- d inside diameter of pipe, in.

The equivalent length includes the actual segment length plus the equivalent lengths for fittings and bends. Valves were not included in the equivalent length but were accounted

for in separate calculations based on their flow coefficients.

The vapor pressure losses were calculated from the following equation (ref. 1):

$$\Delta P_v = 1.34 \frac{vw^2 L \psi}{d^5} \times 10^{-5} \quad (4)$$

where

- $\Delta P_v$  vapor pressure loss, psi
- $v$  vapor specific volume,  $\text{ft}^3/\text{lb}$
- $w$  vapor weight flow rate,  $\text{lb/hr}$
- $L$  equivalent length, ft
- $\psi$  dimensionless factor for surface roughness, viscosity, etc.
- $d$  inside diameter of pipe, in.

The results of hydraulic pressure calculations together with the design flow velocities are listed in table IV. The table also includes the pressure losses in the boiler and main heater as calculated in their respective sections in this report. A pressure-loss allowance of 15 pounds per square inch was allowed for the research items in both the vapor loop and the cooler loop in estimating the required pump performance.

## Primary Heater

The primary heater provides the original source of the heat used to generate the potassium vapor. Heat applied directly to the NaK liquid in the heater loop is then transferred to the potassium in the shell-and-tube boiler. The primary heater supplies 524 000 Btu per hour to preheat and boil the potassium and 141 000 Btu per hour to overcome the system heat losses, a total of 665 000 Btu per hour (195 kW).

The NaK is heated by passing an electrical current through it and its containment pipe; thus, its electrical resistance is used directly to effect a temperature rise. This application of direct heating, compared with other heat-transfer mechanisms, results in a smaller size heater because the size requirement is not controlled by a heat-transfer area. Another advantage of this type of heating, as a result of the small size, is rapid control response that results from the small thermal capacitance.

The primary heater, shown in figure 7, consists of three parallel tubes joined by inlet and outlet headers. The electrical bus-bar connections located in the middle of each tube divide the heater into six parallel sections. The entire unit is encased in ther-

mal insulation to minimize the heat losses and, therefore, to reduce the power requirements. The design details are presented in the following discussion.

Mechanical design. - As indicated previously, each of the six primary heater tubes was formed from seamless HS-25 (cobalt-base alloy) tubing that had an outside diameter of 1 inch, a wall thickness of 0.065 inch, and a length of 66.8 inches. Generous bends (bend radius equals five tube diameters) were used to allow for thermal expansion. The 47-inch dimension between headers (shown in fig. 7) was fixed by the layout of the loop piping. The bus-bar connections at the center of each tube and both the inlet and outlet manifolds were machined from solid HS-25 bar stock and plates. Adapter stubs were machined on each piece to match the tubes for weldments. This technique provided smooth transitions of material cross sections from one component to another, which, in turn, provided good structural integrity and eliminated points of local high electrical resistance that could cause troublesome hot spots.

Since the heater consists mainly of tubing, the stress calculated for the heater tubes was given in the piping section entitled Stress Calculations.

Electrical design. - The required 195 kilowatts of electric power was available at the facility site in the form of a 440-volt, 60-cycle-per-second, 3-phase alternating current. Therefore, a low-voltage alternating-current heater was used that contains two parallel current paths and three electrical connections. The heater was designed so that the fluid inlet and outlet boundaries would be at the same electrical potential to avoid a parallel current path through the remainder of the heater loop. The heater ends were at electrical neutral potential while the center of the heater was at the elevated potential.

A nominal voltage drop of 10 volts across the one heater section was arbitrarily selected to examine the current levels involved. The current through each one of the two required paths was calculated to be 9750 amperes if single-phase alternating-current power is used. By using three-phase power, however, six parallel paths are used, and the current per path is 3250 instead of 9750 amperes.

The three-phase arrangement is given in figure 7. The three parallel tubes above the bus-bar connectors formed one Y-resistance network with the outlet header at an electrical neutral potential (currents were assumed to be equal in each leg). The three tubes below the connector and the inlet header formed a second Y-network that paralleled the upper network. It was assumed that each of the six heater legs would apply an equal amount of heat. The requirement that both the fluid inlet and outlet connections be at the same or neutral potential was satisfied in this arrangement. Note that the three-phase line voltage is 1.7 times larger than the heater leg voltage, but this requirement does not adversely affect the power supply design.

For design purposes, an arbitrary limit of 3000 amperes per heater leg was selected for this heater. It was then necessary to determine the length and cross section of one heater leg that provided the correct electrical resistance needed to apply 1/6 of the total

heat load (195 kW) with 3000 amperes passing through it. The total resistance per leg was calculated to be  $3.6 \times 10^{-3}$  ohm. This resistance per leg, however, was composed of two parallel resistances of equal length formed by the containment pipe and the NaK within the pipe. The sum of these is given by

$$\frac{1}{R_t} = \frac{1}{R_{\text{pipe}}} + \frac{1}{R_{\text{NaK}}} \quad (5)$$

where

$R_t$  total resistance

$R_{\text{pipe}}$  containment-pipe resistance

$R_{\text{NaK}}$  resistance of NaK within pipe

and the resistance per unit length  $L$  is given by

$$\frac{R_t}{L_t} = \frac{\left(\frac{R}{L}\right)_{\text{pipe}} \times \frac{R_{\text{NaK}}}{L}}{\left(\frac{R}{L}\right)_{\text{pipe}} + \frac{R_{\text{NaK}}}{L}} \quad (6)$$

The heater leg resistances per unit length for HS-25 pipe and NaK-78 used in the heater were determined from the ratios of resistivity to cross-sectional area for each pipe size. HS-25 tubing of 1 inch outside diameter and 0.065 inch wall thickness was used for the heater. The values of the resistivity  $\rho$  for the NaK-78 and HS-25 material used were 39.0 and 57.7 microhm-inches, respectively. The resistances per unit length were then calculated to be  $65.6 \times 10^{-6}$  ohm per inch for the NaK and  $302 \times 10^{-6}$  ohm per inch for the pipe. These values, in conjunction with the value of resistance per leg, produce a heater length of 66.8 inches (fig. 7).

Power supply and control system. - The power supply system is basically a matching transformer with controlled input voltage regulation. The transformer matches the 440-volt, three-phase supply to the three-phase terminal voltage necessary to drive 3000 amperes through each of the six heater legs. The maximum terminal voltage of the transformer secondary windings was calculated by using the equation

$$E = \sqrt{3} Z I \quad (7)$$

where

E terminal voltage, V

Z total impedance per phase,  $\Omega$

I current, A

The total calculated resistance per phase was  $1809 \times 10^{-6}$  ( $1800 \times 10^{-6} \Omega$  in the heater tubes and  $9.4 \times 10^{-6} \Omega$  in the bus bars), and the total calculated reactance per phase was  $342 \times 10^{-6}$  ohm ( $294 \times 10^{-6} \Omega$  in the heater tubes and  $48 \times 10^{-6} \Omega$  in the bus bars), which gives a total impedance per phase Z of  $1842 \times 10^{-6}$  ohm. All reactances were assumed to be lagging or inductive. This value of impedance for a heater leg current of 3000 amperes produced a calculated value of voltage near 20 volts.

Experience has indicated the need for providing some overcapacity in the transformer power rating to allow for fabrication tolerances in the primary heater and contingent bus-bar losses. The performance specifications drawn for procurement of the three-phase transformer were as follows:

Normal rating . . . . .	225 kVA, 60 cycle
Primary winding . . . . .	440 V (wye)
Secondary winding . . . . .	20 V (delta)
Maximum secondary current . . . . .	6200 A/phase

Two 10-percent auxiliary primary taps were provided on each phase to give additional choices of 22 and 24 volts from the secondary at the same primary rated input. The selection of three-phase winding arrangements of a wye primary and delta secondary was considered good design practice for stepdown transformers.

The three bus-bar connections between the heater and the transformer were essentially the same. The bus arrangement was simple and short, but each bus bar was about 8 feet long. At any cross section through a bus bar, the copper area is made up of four  $1/4$  by 6 inch bars.

Control of the primary heater power was accomplished by analog variations of the transformer terminal voltage. The voltage was varied and set either manually or automatically with a temperature feedback loop. A block diagram of the control circuit is shown in figure 8(a). Separate saturable core reactors were connected on each phase between the 440-volt, 60-cycle-per-second, alternating-current source and the transformer terminals. The saturable core reactors, which are variable inductive reactances, introduce a variable voltage drop between the transformer and the line so that the terminal voltage can be regulated by the transformer. The direct-current control voltages to the reactors were supplied by three separate 300-watt magnetic amplifiers, which amplified direct-current signal of 3 to 5 milliamperes to 5 to 75 volts of direct current. Variable

autotransformers were connected internally to the magnetic amplifiers to provide a variable gain control for balancing the three-phase currents in the primary heater. The transformers also provided adequate control sensitivity for low turndown heats. The drive signal of 0 to 5 milliamperes for the magnetic amplifiers was provided by a three-mode electronic controller having proportional band, rate, and reset modes. The inputs of the magnetic amplifiers were connected in series to match each one to a common controller output. Thus the total three-phase power was regulated by a single control signal. The control signal was set manually with a variable resistance potentiometer or set automatically by the set-point temperature of the NaK at the outlet of the primary heater. A photograph of the power supply area of the facility is shown in figure 8(b).

Pressure losses. - The hydraulic circuit of the primary heater was considered divided into three parallel paths, each containing two 66.8-inch legs in series. The calculated pressure losses across the heater at the maximum NaK flow of 105 gallons per minute were as follows:

Tubing, 12-foot length, 1-inch diameter, 0.065-inch wall, psi . . . . .	5.7
Bends, three 180°, psi . . . . .	2.1
Header to tube entrance, psi . . . . .	<u>4.1</u>
Total, psi . . . . .	11.9

## Boiler

Description. - The task of the boiler was to vaporize liquid potassium for the vapor loop over a temperature range from 1300° to 1725° F at flow rates up to 590 pounds per hour with a variable vapor quality of 75 to 100 percent. As indicated previously, the boiler was mounted in a horizontal position to minimize the effect of gravity on its operation. The general configuration of the boiler is shown in figure 9(a). It is a once-through counterflow shell-and-tube-type heat exchanger with NaK heating fluid in the shell and potassium inside the tubes. The boiler was shaped like a hockey stick to allow for differential expansion between the shell and the tubes. This shape reduced the tube thermal strain and the subsequent tube-to-tube sheet shear force. The spherical connections for the heating fluid, which were a patented design feature of the design contractor, minimized stress concentrations in these areas. The overall length from tube sheet to tube sheet was 169.5 inches. The boiler material was HS-25 throughout with an all-welded construction. All the parts other than the tubes and the outside shell cylinders were machined from wrought plates or bar stock. The tubes were seamless, but the 4-inch-inside-diameter outer-shell cylinders were welded because at that time tubing processors could not fabricate this size of seamless tubing from HS-25 except on an experimental

best effort basis. The cylinders were fully X-rayed to establish the integrity of the weld and were cold drawn to the finished diameters to improve the weld zone by cold working to a wrought state.

The boiler contains 43 parallel tubes, each with an outside diameter of 0.375 inch and a wall thickness of 0.035 inch, drawn from seamless tubing having a diameter of  $1\frac{1}{2}$  inches and a wall thickness of  $\frac{1}{8}$  inch. The tube size selected was a practical compromise between minimum number of tubes and maximum diameter necessary to produce meniscus forces sufficiently large to overcome gravity forces and to establish a liquid-to-vapor interface across the horizontally oriented tube. The number of tubes was established by the total inside cross-sectional area and a vapor velocity of 160 feet per second at 1600° F.

Both ends of each tube were welded into tube sheets. Before the welding operation, the tube sheets were trepanned around each hole to provide a material cross section similar to that of the tube. The tubes were slid into the holes and end-welded to the sheet. A cross-sectional detail of the tube sheet at one tube is sketched in the insert of figure 9(a), and the finished welding of one tube sheet is shown in figure 9(b). The trepanned grooves are not apparent in the photograph because they were filled with weld material during the final pass. Orifices with 0.040-inch diameter were inserted and welded into the inlet of each boiler tube. The orifice installation is shown in the insert of figure 9(a). Boiler designers and experimenters have discovered empirically that flow restrictions at the entrances of boiler tubes minimize intertube flow and help to stabilize the outflow from once-through-type boilers.

The tubes were held in position inside the shell by separator bars welded to a ring that fit the inside diameter of the shell. The photograph in figure 9(c) shows one set of these bars. Rings of these bars were located at about six 9-inch intervals along the boiler length and were alternately rotated 30° from each other to form a lattice. Figure 9(d) shows an overall view of the boiler tube assembly without the outer shell cylinder. The series of rings located in the main cylinder section as well as the solid rods that fill the spaces left by the omission of partial tubes on the outer row of the tube bundle are also shown in the photograph.

Heat transfer. - Although the specifications required a vapor temperature of 1725° F, the general conditions selected for the design were to isothermally vaporize 590 pounds per hour of potassium at 1600° F with a NaK flow of 105 gallons per minute. The design was examined for three different NaK inlet temperatures, 1800°, 1735°, and 1682° F, which covered the potential operating range. The heat of vaporization of the potassium corresponds to a total heat flow of 510 000 Btu per hour, which corresponds to a drop in temperature of 75° F for the NaK at a flow of 105 gallons per minute. Since the tube size and number of tubes had already been established, the only dimension to be obtained was the tube length, which was determined from the calculated required heat-transfer area.

The first step in the design was to estimate the local heat-transfer coefficients to the wall for the NaK and for the boiling potassium.

Local overall heat-transfer coefficients were derived by the contractor in the design of the boiler and will be presented in the following calculations. The overall local heat-transfer coefficient is the sum of three series thermal conductances as shown in the following equation:

$$\frac{1}{U_o} = \frac{1}{h_{NaK}} + \frac{1}{h_w} + \frac{1}{h_k} \quad (8)$$

where

$U_o$  overall coefficient Btu/(hr)(ft<sup>2</sup>)(°F)

$h_{NaK}$  film coefficient between NaK liquid and boiler tube wall, Btu/(hr)(ft<sup>2</sup>)(°F)

$h_w$  coefficient across the tube wall, Btu/(hr)(ft<sup>2</sup>)(°F)

$h_k$  film coefficient between boiling potassium fluid and tube wall, Btu/(hr)(ft<sup>2</sup>)(°F)

The heat-transfer coefficient from the hot NaK to the outside surface of the boiler tubes  $h_{NaK}$  was estimated from the following correlation:

$$N_{Nu} = 0.01915 N_{Pe}^{0.885} \quad (9)$$

where

$N_{Nu}$  Nusselt number

$N_{Pe}$  Péclet number

This correlation has been verified experimentally by the design contractor in a similar heat exchanger using NaK as the heating fluid. Equation (9) was rewritten in terms of physical quantities as

$$h_{NaK} = 0.01915 \left( \frac{k}{D_e} \right)^{0.115} (C_p \rho V)^{0.885} \quad (10)$$

where

$k$  NaK thermal conductivity, 14.0 Btu/(hr)(°F)(ft)

$D_e$  effective diameter of boiler tube, 0.0254 ft



$C_p$  NaK specific heat, 0.219 Btu/(lb)(°F)

$\rho$  NaK density, 40 lb/ft<sup>3</sup>

$V$  NaK velocity, 24 500 ft/hr

For the design calculation, it was assumed that the NaK was uniformly distributed over the 43 boiler tubes and that a single value of shell-side coefficient taken at a representative mean bulk temperature of 1763° F and at a flow rate of 105 gallons per minute would suffice for the design. For these conditions, a value of  $h_{\text{NaK}}$  of 2101 Btu/(hr)(°F)(ft<sup>2</sup>) was calculated.

The transfer coefficient across the tube  $h_w$  was also calculated as a single mean value. At a mean temperature of 1763° F, the value of thermal conductivity for HS-25 was taken as 15.5 Btu/(hr)(°F)(ft). For a tube wall thickness of 0.035 inch, a value for  $h_w$  of 5220 Btu/(hr)(°F)(ft<sup>2</sup>) was calculated.

For the boiling inside the tubes, entering and exit conditions of boiling film transfer coefficient  $h_k$  were considered. The entering value was based on laminar flow of liquid at zero percent vapor, and the exiting value was based on turbulent flow of 100 percent saturated vapor. Because boiling potassium coefficients were not predictable, they were conservatively assumed to vary between these two conditions dependent on the vapor quality.

The film coefficient at the inlet (0 percent vapor) was calculated to be 2230 Btu/(hr)(ft<sup>2</sup>)(°F). In the absence of better data, the value of  $h_k$  at the boiler inlet was based on the following equation for properties of potassium at 1600° F:

$$N_{\text{Nu}} = \frac{h_k D}{k} = 3.65 \quad (11)$$

where

$D$  diameter of boiler tube, ft

At the boiler outlet the film coefficient  $h_k$  was estimated from the Sieder-Tate correlation (ref. 2):

$$N_{\text{Nu}} = 0.023 N_{\text{Re}}^{0.8} N_{\text{Pr}}^{0.4} \left( \frac{\mu_w}{\mu_b} \right)^{0.14} \quad (12)$$

where

$N_{\text{Re}}$  Reynolds number,  $GD/\mu_b$

$N_{Pr}$	Prandtl number, $C_p \mu_b / k$
$\mu_w$	vapor viscosity evaluated at the tube wall temperature
$\mu_b$	vapor viscosity evaluated at the saturation temperature
$G$	mass velocity

The potassium was assumed to be at a saturation temperature of 1600° F and the tube wall at a temperature of 1750° F. A value of  $h_k$  at the boiler outlet (100 percent vapor) was then calculated to be 17.8 Btu/(hr)(ft<sup>2</sup>)(°F).

By substituting the calculated values of film and conductive heat-transfer coefficients into equation (8), the overall values of  $U_o$  at each end of the boiler tubes were determined. At the entrance (0 percent vapor), a value of overall coefficient  $U_o$  of 860 Btu/(hr)(ft<sup>2</sup>)(°F) was calculated. At the outlet, the vapor film coefficient was the controlling factor with a calculated value of 17.5 Btu/(hr)(ft<sup>2</sup>)(°F) for  $U_o$ .

Between these limits, four distributions of overall coefficient were selected for preliminary design purposes because the vapor quality varied from 0 to 100 percent in the boiler tube. These distribution curves are presented in figure 10. Curves A, B, and C are based on NaK inlet temperatures of 1800°, 1735°, and 1682° F, respectively. Curve D is based on the arbitrary assumption that the overall coefficient is constant at 860 Btu/(hr)(ft<sup>2</sup>)(°F) from a quality of 0 to 75 percent and constant at 17.5 Btu/(hr)(ft<sup>2</sup>)(°F) from a quality of 75 to 100 percent. Curve D was assumed to be independent of the NaK heating temperature.

The next step in the design was to calculate the tube lengths required from the overall coefficients given by the distribution curves. The method used was to divide the boiler tube into zones of quality increments from 0 to 100 percent. These zones correspond to zones of equal quantities of heat transfer. The incremental length for each zone was calculated from the average conditions in each increment from the equation

$$\Delta L = \frac{H \Delta x}{n \pi D U_o \Delta T} \quad (13)$$

where

$\Delta L$	incremental length, ft
$H$	total heat transferred, Btu/hr
$\Delta x$	incremental quality, percent/100
$n$	number of boiler tubes
$D$	inside diameter of boiler tube, ft

$\overline{U}_O$  average overall heat-transfer coefficient in increment  $\Delta x$ , Btu/(hr)(ft<sup>2</sup>)(°F)

$\overline{\Delta T}$  average driving temperature from NaK liquid to potassium vapor in increment  $\Delta x$ ,  
 $T_{NaK} - T_K$ , °F

A linear distribution of the driving temperature  $\Delta T$  with quality was used because the potassium temperature was assumed constant at 1600° F and because the NaK temperature was assumed to decrease uniformly with increasing vapor quality. To determine average values of  $\overline{U}_O$  and  $\overline{\Delta T}$ , a plot of  $1/\overline{U}_O \overline{\Delta T}$  against vapor quality  $x$  was made, and the average value for an increment of vapor quality was read. The calculations of  $\Delta L$  were based on the following constant values:  $H = 510\,000$  Btu per hour,  $n = 43$  tubes, and  $d = 0.0254$  feet.

The total length then is given by

$$L = \sum_{x=0}^{100 \text{ percent}} \frac{\Delta L}{\text{percent}} \quad (14)$$

Calculated tube lengths for the four types of distribution curves are given in table V. On the basis of these values the boiler was constructed with a tube length (between the NaK inlet and outlet connections) of 12.8 feet (154 in.) as shown in figure 9(a).

Pressure losses. - The pressure losses of the liquid NaK in the shell side of the boiler were calculated at a maximum flow rate of 105 gallons per minute. Results of the calculations, performed by the contractor, are given in the following table:

Friction loss, psi . . . . .	2.68
Header loss (flow turning 90° in ball sections), psi . . . . .	2.15
Loss across tube separators, psi . . . . .	<u>1.98</u>
Total, psi . . . . .	6.81

The pressure losses in the potassium flowing through the boiler were calculated from conventional turbulent pipe friction and orifice correlations using average fluid conditions. It was also assumed that a single friction coefficient applied throughout and that no slip occurred in the 2-phase regime. A summary of the pressure losses calculated at a flow of 590 pounds per hour is given in table VI.

Stress calculations. - The boiler shell was analyzed in separate sections; (1) the main cylinder, (2) the spheres, and (3) the cylindrical end of the short leg. Each part was assumed to have a uniform wall thickness and radius and to be at a uniform temperature of 1800° F. A thickness of 0.010 inch was deducted from the specified shell thicknesses to allow for oxidation of the exterior surface. The hoop (or membrane) stress

was calculated from the following equations:

For cylinders:

$$\sigma_H = \frac{PR}{h - 0.010} \quad (15a)$$

For spheres:

$$\sigma_H = \frac{PR}{2(h - 0.010)} \quad (15b)$$

where

- $\sigma_H$     hoop stress, psi  
P       pressure differential across the shell, 70 psi  
R       mean radius of the shell, in.  
h       thickness of the shell, in.

The safety factor in this case was calculated as the ratio of an allowable stress limit to the calculated stress. The value of allowable stress was the estimated stress to rupture at 1800° F (table II) multiplied by a weld efficiency of 0.60. The resulting calculated stresses and safety factors are summarized in table VII(a). The safety factors shown are above the value of 3.0 that was required by the specifications.

The tube sheets were analyzed as perforated plates subject to a uniform load. The thickness was assumed to be constant, and any effects of the tube welds were neglected. The pressure across the sheet was taken as the highest pressure expected in the shell minus the lowest pressure expected in the tube headers. The stress was calculated at two temperature levels of 1600° and 1800° F, corresponding to temperatures of the inlet sheet and the outlet sheet, respectively. The bending stress was then calculated from

$$\sigma_b = \frac{1.24 PR^2}{h^2} \frac{S}{S - 0.952 D} \quad (16)$$

where

- $\sigma_b$     bending stress, psi  
P       pressure difference across the tube sheet, 80 psi  
R       radius of the circular sheet, 2.21 in.

S center to center distance between holes, 0.51 in.

D diameter of the holes in the sheet, 0.375 in.

The calculated safety factors were based on an allowable stress-to-rupture stress of 4200 psi at 1800° F (outlet) and 10 000 psi at 1600° F (inlet). The calculated values for the two locations are listed in table VII(b). Although the inlet tube sheet is thinner and subsequently more highly stressed, it still has an adequate safety factor because of the higher strength of the material at the lower temperature, 1600° F.

The boiler tubes were analyzed for effective hoop stress and buckling pressure. The hoop stress was found from equation (15a) above with an allowance of 0.007 inch made for corrosion of the tube wall. The actual tube dimensions were an outside diameter of 0.375 inch and a wall thickness of 0.035 inch. The critical external buckling pressure across the tube wall  $P'$  was found from the equation (ref. 3)

$$P' = \frac{E(h - 0.007)^3}{4R^3(1 - \nu^2)} \quad (17)$$

where

$P'$  critical pressure, psi

$E$  elastic modulus,  $24 \times 10^6$  psi

$h$  tube wall thickness, 0.035 in.

$R$  mean tube radius, 0.170 in.

$\nu$  Poisson's ratio, 0.3

The safety factor was based on a differential pressure of 73 pounds per square inch across the wall. The results of the boiler tube stress analysis are as follows: hoop stress, 405 pounds per square inch with a safety factor of 10.35; critical buckling pressure 29 460 pounds per square inch with a safety factor of 382.0.

## Superheater

The superheater was designed to provide up to 75° F of superheat to saturated potassium over a range of inlet temperatures from 1300° to 1725° F at a maximum flow of 590 pounds per hour. These conditions represent a maximum heat input of 6800 Btu per hour. The superheater consists of a 23-foot-long section of 2-inch, schedule 40, HS-25 pipe that was connected to the boiler exit. The pipe was radiantly heated with semicylindrical clamshell-type electric heaters covered by high-temperature insulating material. The 2-inch pipe size was established by a maximum vapor velocity of 160 feet per second

at 1600° F. The pipe wall thickness requirement (schedule 40) as well as pipe stress and pressure drop considerations were discussed earlier in the section entitled Piping.

The design of the superheater was based on the heating of a straight run of 2-inch-diameter pipe at an essentially uniform heat flux. The first design criterion was to limit the surface of the pipe to a maximum of 1900° F at the superheater exit. This requirement limited the design temperature drop between the inner surface of the pipe and the potassium vapor to 99° F (allowing for a temperature drop of 1° F across the pipe wall). The required heat-transfer surface area for the pipe inner surface was then determined from the required heat input (6800 Btu/hr) and the fluid film coefficient of the vapor flowing in the pipe. The film coefficient was determined from the standard correlation for fully developed turbulent gas flow (ref. 2):

$$\frac{h_k D}{k} = 0.023 \left( \frac{GD}{\mu} \right)^{0.8} N_{PR}^{0.4} \quad (18)$$

where

$h_k$  film heat-transfer coefficient, Btu/(hr)(ft<sup>2</sup>)(°F)

$D$  inside diameter of pipe, 0.172 ft

$k$  thermal conductivity of potassium vapor at 1760° F, 0.0055 Btu/(hr)(ft)(°F)

$G$  mass velocity of potassium vapor, 25 350 lb/(hr)(ft<sup>2</sup>)

$\mu$  viscosity of potassium vapor at 1760° F, 0.0275 lb/(hr)(ft)

$N_{PR}$  Prandtl number, 0.73

A film coefficient  $h_k$  of 9 Btu/(hr)(ft<sup>2</sup>)(°F) was calculated based on the fluid properties given. A Prandtl number of 0.73 was used because some of the vapor properties were calculated from this number (ref. 4). The calculated heat-transfer area indicated a pipe length of 15 feet was necessary, but a 50-percent safety factor was applied to allow for uncertainties in the estimated value of film coefficient; thus, the superheater was constructed 23 feet long.

The total electrical power requirement was determined as the sum of the power required to superheat the potassium flow and that lost through the insulation. A maximum power of 2000 watts was required to superheat 590 pounds per hour of saturated potassium vapor. From the properties of the insulating material used, the heat loss was estimated to be about 150 watts per lineal foot at 1800° F. This indicated a maximum insulation loss of 3450 watts for a total power requirement of 5450 watts.

A commercial heater 12 inches in length and capable of 2100° F operation was se-

lected as the basic heating element. Forty-five of these semicylindrical units were required to provide a number that was a multiple of three to balance the three-phase electrical power. The heaters were placed end-to-end to a total length of 23 feet. The electrical power was supplied from a 440-volt alternating-current three-phase source and was controlled with an adjustable autotransformer that varied the heater terminal voltage smoothly from 0 to 110 percent of the supply voltage.

The construction details of the heater are given in figure 11. The clamshell heaters, were centered on the pipe with refractory spacers and clamped into place with metal bands. The heaters were covered with about 2 inches of soft high-temperature insulation. The entire superheater assembly was then encased in 6-inch-thick asbestos insulation. The heater wires were retained in a refractory mold by refractory cement or filler that was about 1/8-inch thick.

The operating temperature of the heater was determined in the following manner. The problem was to estimate the overall driving temperature from the heater wire to the potassium vapor at the hottest point, the superheater exit. The heat transfer from four parts had to be considered: (1) conduction from the wires through the refractory shell, (2) radiation from the refractory shell heated by the wires to the outside pipe surface, (3) conduction through the pipe wall, and (4) convection from the inside pipe surface to the potassium vapor. The radiation heat transfer was based on assumed surface emissivities of 0.5 for the heater refractory material and 0.8 for the outside surface of an oxidized pipe. The radiative driving temperature was calculated from the following equation (ref. 2):

$$T_h^4 - T_w^4 = \left( \frac{1}{E_h} + \frac{1}{E_w} - 1 \right) \frac{H}{\sigma A} \quad (19)$$

where

$T_h$  heater temperature,  $^{\circ}\text{R}$

$T_w$  pipe outer surface temperature,  $^{\circ}\text{R}$

$E_h$  emissivity of heater wire, dimensionless

$E_w$  emissivity of pipe surface, dimensionless

$H$  total heat transferred to superheat potassium, 6800 Btu/hr

$\sigma$  Stefan-Boltzman constant,  $\text{Btu}/(\text{hr})(^{\circ}\text{R}^4)(\text{ft}^2)$

$A$  area of superheater pipe surface,  $12.5 \text{ ft}^2$

The temperature drop from the wire was based on a 1/8-inch refractory length and a thermal conductivity of  $1 \text{ Btu}/(\text{hr})(\text{ft})(^{\circ}\text{F})$ . That across the 0.154-inch pipe wall was based on a thermal conductivity of  $16 \text{ Btu}/(\text{hr})(\text{ft})(^{\circ}\text{F})$ .

With a heat flux of  $544 \text{ Btu}/(\text{hr})(\text{ft}^2)$  based on 23 feet of 2-inch pipe and a heat input of 6800 Btu per hour, an overall temperature differential of  $81^\circ \text{ F}$  was calculated. The temperature differences of the various processes that comprised the overall heat transfer are as follows:

Conduction through refractory material, $^\circ \text{F}$ . . . . .	6
Radiation through air gap, $^\circ \text{F}$ . . . . .	13
Conduction through pipe wall, $^\circ \text{F}$ . . . . .	1
Vapor film ( $h_k = 9 \text{ Btu}/(\text{hr})(\text{ft}^2)(^\circ \text{F})$ ), $^\circ \text{F}$ . . . . .	<u>61</u>
Total, $^\circ \text{F}$ . . . . .	81

These calculations indicated that a heating wire temperature of  $1881^\circ \text{ F}$  was adequate to attain a vapor temperature of  $1800^\circ \text{ F}$ . This temperature was well below the rated heater temperature of  $2100^\circ \text{ F}$ . Also, the maximum pipe temperature calculated to be only  $1862^\circ \text{ F}$  which was well below the limit of  $1900^\circ \text{ F}$ .

### Pumps

The liquid-metal pumps chosen for the facility are Faraday-type electromagnetic alternating-current conduction pumps. This type of pump has no moving mechanical parts, and consequently no seals are necessary to restrain hot liquid metal. This pump also provides stepless flow control from 0 to 100 percent of rated flow by continuous variation of terminal voltage. The main disadvantages are that Faraday-type electromagnetic pumps are very large and heavy compared with mechanical pumps of the same capacity, and, in addition, the pumping efficiency is very low (5 to 10 percent), especially when the pump is working against high heads. The pumps, however, are "workhorse" components for this facility, and the simplicity of operation was considered to outweigh such disadvantages.

The electromagnetic pump operates on the same principle as an electric motor. The liquid-metal stream flowing through the pump acts in the same manner as the solid electrical conductor that rotates in an electric motor. The stream is directed through the pump by a single straight length of pipe called the pump duct. A diagram demonstrating this principle is given in figure 12. When both magnetic flux and electrical current are passed transversely across the duct, an accelerating force is applied to the liquid-metal stream. The current is applied to the duct by two diametrically opposed bus bars that are brazed to the duct. Also diametrically opposed but at right angles and coplanar to the bus bars are two pole pieces that provide the magnetic flux. Since the electrical current, magnetic flux, and accelerating force are three mutually perpendicular vector quantities generated from an alternating or time-varying voltage source, they must be a maximum at the same instant for the best efficiency. Electrical phase differences seri-



ously reduce efficiency. The inductive phase lag is compensated for by capacitors connected across the pump terminals.

A summary of the requirements for the three pumps used in the facility is given in table VIII. There are two large-capacity pumps and one small-capacity pump. Except for the supply voltage, the requirements were established by the respective maximum operating condition of each loop. The general power supply to the facility was 440 volts alternating current so that the large pumps could be powered directly. The small pump was furnished with 240 volts of alternating current by means of a matching transformer.

The hydraulic characteristics of both the loop system and the pump can be used to show how the pump matches the system and also how it acts as a flow control. A family of pump-performance curves showing the relation of volume flow and pressure rise at constant terminal voltage is given for each of the two pump sizes in figures 13(a) and (b). The performance at the maximum allowable terminal voltage is depicted by the solid curve supplied by the pump manufacturer. Other constant voltage lines exist, as implied by the dashed lines on the plot. The loop maximum flow requirement is shown to lie within the capabilities of the pump. A parabolic curve representing the pressure-rise - volume-flow characteristic of the loop is drawn through the maximum operating point in figure 13(a) and (b) to show the line on which the pump is to operate. It may be seen that this operating line crosses each constant voltage line only once. Consequently, the system flow can be varied by merely varying the terminal voltage on the pump. A line-voltage variation of 0 to 110 percent was accomplished by using adjustable autotransformers.

A photograph of the heating loop pump with identification of the major components is shown in figure 6. The cooling-loop pump was identical in appearance, and the vapor-loop pump was similar except for size. The pump shown in figure 6 was constructed with two pumping stages; consequently, there are two pairs of field coils and two pairs of armature attachments on the pump duct. The armature connections of the two stations are interconnected by a common terminal. These terminals from the secondary windings of two current transformers were referred to earlier (only one is visible in the picture). The current transformer primary windings were wound and interconnected such that their secondary currents were additive. The large pumps were equipped with air blowers connected to the cooling ducts shown in the photograph. Each of the two large pumps weighed 800 pounds, and the small one weighed 90 pounds.

## Liquid-Metal Valves

This discussion on valves is confined to those valves that were in contact with the alkali-metal fluid. Other valves that controlled the flow of service fluids were all off-the-shelf types with no special features or modification requirements. The liquid-metal

valves used in this facility have frequently been used for such service, and no basic developments were required for this application. However, some specific adaptations were made, such as the use of high-temperature materials for the plug and seat and the seal welding of the plug assembly. The shutoff and throttling operators on the remotely controlled valves were completely pneumatic and had stainless-steel supply lines inside the enclosure.

The three different styles of valves used are shown in sectional drawings of the valve bodies in figures 14(a), (b), and (c). Valve style 1 (fig. 14(a)) was used for 1/2-inch or smaller lines for both shutoff and throttling services. It had a small valve lift of about 1/8 inch, which promoted a higher reliability of the bellows because shorter and more stable bellows could be used. Fine throttling control was obtained even with the small lift.

Valve style 2 (fig. 14(b)) was used in only with the  $1\frac{1}{2}$ -inch pipe size. Its only salient feature was that the plug guides were located on the plug. To withstand the high operating temperature, these guides, like the seat and the plug, were made from high-temperature alloys (Haynes Stellite) to prevent fusion welding at elevated temperatures.

Valve style 3 (fig. 14(c)) was used in the 2-inch pipe size. The unique feature of style 3 was its shutoff mechanism. A guide cage moved a ball across the flow path and wedged it into a conical seat where it sealed off the flow. As the ball was removed from the seat during the opening operation, it revolved and was washed by the system fluid. When reseated again, it contacted the seat with different surfaces, thus cleaning the seating surfaces and minimizing wear during valve operation.

Valve styles 2 and 3 used long lifts (they are much larger than valve style 1); consequently, very long bellows assemblies were required, which made them much more vulnerable to bellows failures than valve style 1.

In all types, the valve stems were sealed by an argon-backed seamless bellows. By pressurizing one side of the bellows with argon to slightly above line pressure, bellows stresses were minimized, and a rupture would cause the argon gas to leak into the system rather than allowing hot liquid metal to leak out of the valve. Two of the three models shown use the pressurizing gas inside the bellows, and the other model uses the gas outside the bellows. In each style a compressible high-temperature packing was used to prevent excessive leakage of gas around the valve stem.

All valve parts and bodies were machined from rolled or forged billets. The plugs and seats were made from different Haynes Stellite high-temperature alloys to prevent fusion welding at elevated temperatures. The bellows and valve stem subassemblies were seal-welded to the valve body where a conventional gasket would normally have been located. To disassemble the valve, this weld had to be ground away.

## Air Cooler

The function of the air cooler (see fig. 3) is to transfer up to 180 kilowatts of heat absorbed by the NaK coolant from the condenser to atmospheric air for final disposition. A schematic of the crossflow air cooler and control damper valve is shown in figure 15. The cooler is a piece of commercially available finned pipe bent into a hairpin shape. The advantage of the design is that it consists of a continuous pipe without headers. Thus no header weldments are required and no axial thermal expansion forces are encountered.

The finned tubing was supplied by the manufacturer assembled in a section of duct work, 72 inches wide by 21 inches high by 4 inches deep. The assembly was mounted on the inside of the enclosure with a 90° elbow section attached to the duct inlet to provide a flush inlet on the outside vertical wall of the enclosure. The cooling air supply was drawn from outside the enclosure rather than from the inside because of possible contamination of the inside air from alkali metal oxides. The outlet of the duct was fitted to a transition duct section (fig. 15) to match it to the 8-inch-diameter air-suction line. The air was drawn over the cooler and through the duct by an exhaust fan located in the basement of the building. The airflow was regulated by an air-motor-operated butterfly damper valve. The damper position was controlled either manually or automatically by a two-mode pneumatic controller. During automatic control operation, the airflow was regulated to maintain the NaK outlet temperature at a desired set value.

The finned tube length and ducting were designed to meet the requirements given in the following table:

Condition	Liquid-metal side (NaK)	Air side
Inlet temperature, °F	1 500	100
Maximum outlet temperature, °F	1 400	600
Inlet pressure, psia	65	14.7
Maximum pressure loss	5 psi	10 in. H <sub>2</sub> O
Weight flow rate, lb/hr	31 000	10 000

The cooler was sized for a heat load of 200 kilowatts (683 800 Btu/hr) to provide extra capacity and a wide range of operation. The required fin area was calculated from the mean temperature difference to the air of 1200° F. An overall heat-transfer coefficient to the air of 8.4 Btu/(hr)(ft<sup>2</sup>)(°F) was also assumed based on the experience of the design contractor with finned tubing. A required fin surface area of 68.4 square feet was then calculated. The finned tubing selected was fabricated from 1½-inch-diameter, schedule 40, type 316 stainless-steel pipe with six fins per inch. The fins were 3.40 inches in diameter and 0.030 inch thick. The pipe was grooved on the outside to receive the

fins, which were brazed in place. The finned pipe provides 6.4 square feet of fin area per foot of length; therefore, 10.7 feet were required. The heat exchanger was fabricated in two 6-foot-long sections.

## Oxide Control and Indicating System

The three liquid-metal loops were provided with an oxide removal system capable of purifying the various liquid metals to impurity levels less than 20 parts per million. The heater and cooler loops which utilize NaK are also provided with an oxide indicating apparatus called a plugging indicator. A plugging-type oxide indicating apparatus was not used in the potassium test loop since the solubility of oxygen in potassium at the freezing point is higher than the desired maximum oxygen content during system operation. Oxide content of the test loop was determined by a chemical analysis of potassium samples drawn from this loop during operation.

The heater-loop and cooler-loop oxide control and indicating systems (OCI) are generally similar in that each system contains a hot trap, a cold trap, and a plugging indicator; all components and piping of the OCI system are trace heated. A block diagram of the heater-loop OCI system is shown in figure 16(a) and a photograph of the installed system is shown in figure 16(b).

In the heater loop, the liquid metal enters the OCI system through a loop bypass line downstream of the liquid-metal pump and returns to the system at the suction side of the pump. Once in the bypass line, the liquid metal can be diverted to either of three circuits. Depending on the valve arrangement, the liquid metal enters the hot trap, the cold trap, or the plugging indicator. The flow through each component is measured by an electromagnetic flowmeter and can be varied between 0 and 3 gallons per minute by a pneumatic-operated control valve in each circuit. The first available flow path is to the hot trap. The hot trap is a 2-gallon vessel containing columbium shavings as an oxygen-getter to remove oxygen from the system. Hot trapping of the liquid-metal oxide was necessary when an oxide content of less than 20 parts per million is required. Hot trapping is a much slower method of oxygen removal than cold trapping and is rate limited by oxygen diffusion into the getter material. The rate is dependent on the temperature of the hot trap, which is usually maintained at loop temperature by radiant heating by clamshell-type electric heaters.

The flow to either the cold trap or the plugging indicator (fig. 16(a)) first passes through an economizer, which is essentially a counterflow shell-and-tube type heat exchanger. The hot liquid metal enters the tubes of the economizer and loses its heat to the liquid returning from either the cold trap or the plugging indicator. This process serves two purposes: it reduces the temperature of the hot liquid prior to the final cool-

ing necessary for cold trapping or for making a plugging run, and, at the same time, the process raises the temperature of the liquid metal returning from these components to the main loop.

The cold trap is a 5-gallon vessel filled with a stainless-steel wire mesh. Room exhaust system air is used for maintaining the cold trap at an operating temperature of 200° F. The temperature of the NaK entering the cold trap is reduced to 200° F, which corresponds to an oxide saturation point of 20 parts per million. Excess oxides precipitate out of the liquid metal and deposit on the stainless-steel wire mesh. The purified liquid is then returned to the main loop through the economizer. The entire NaK inventory can be processed by the cold trap every 15 minutes.

The plugging indicator, shown schematically in figure 17, consists of four 0.035-inch-diameter orifices equally spaced on a 0.25-inch-diameter circle and centered around a 0.06-inch-diameter orifice. Flow rate is measured downstream of these orifices. The liquid metal first flows at a constant flow rate through a fin-and-tube type heat exchanger cooled by cooling air. The cooling air flow, controlled by a pneumatic controller, gradually lowers the liquid-metal temperature until it reaches a point corresponding to the equilibrium solubility of the oxides in the liquid metal. As the temperature drops below the saturation temperature, oxides begin to precipitate and deposit on the orifices, obstructing the flow of liquid. When this obstruction occurs, a sharp drop in flow rate is indicated, and, at this same instant, the temperature of the liquid metal at the orifices is noted. Both the liquid-metal flow rate and temperature at the orifices are recorded simultaneously on a continuously indicating and recording potentiometer. This temperature is then used together with the temperature-against-solubility curve for the liquid metal involved to obtain the oxide content. The solubility curve for NaK-78 is shown in figure 18. The orifices are never allowed to plug completely. Once the plugging temperature is obtained, the cooling of the liquid is discontinued, and heat is immediately applied to the orifices and to the heat exchanger. Opening the valve in the bypass line permits fresh liquid, at a much higher temperature and flow rate, to wash over the top of the orifices dissolving the deposited oxides. The liquid is then returned to the main loop through the economizer.

The cooler-loop OCI system differs from the heater-loop OCI system only in the method of precooling the liquid before it enters the cold trap and the plugging indicator. The cooler loop uses an air-cooled finned-tube heat exchanger at the inlet as a precooler instead of the economizer. A photograph of the cooler-loop OCI system is shown in figure 19.

As indicated previously, the potassium test-loop oxide control system uses only a hot trap. The hot trap is a 3-gallon stainless-steel vessel containing titanium as an oxygen-getter material. The liquid enters the hot trap downstream of the liquid-metal pump and returns to the system at the suction side of the pump. The hot trap is radiant-

heated with clamshell-type electric heaters and is maintained at loop temperature during operation.

## Vacuum Chamber

The facility test vacuum chamber was sized to test a potassium radiator dissipating 150 kilowatts of heat at 1400° F in a vacuum environment. It consists basically of a horizontally oriented cylindrical chamber with an inside diameter of 8 feet and a length of 18 feet (fig. 20). The chamber is attached to the loop at the test-loop enclosure. Provision was included in the original design of the chamber for vacuum operation from  $10^{-3}$  to  $10^{-7}$  millimeter of mercury.

The vacuum chamber was constructed in two sections, a fixed-head section and a retractable-chamber section, as shown in figure 20. The retractable chamber section can be rolled on guide rails away from the fixed head section to permit installation and checkout of the test radiator. The two sections are held together with a quick-disconnect hydraulic-actuated clamp. Double O-rings are used to vacuum-seal this joint as well as all the flanged connections and passthroughs for operation at pressures as low as  $10^{-7}$  millimeter of mercury. The fixed head section is provided with four 32-inch-diameter flanges (two on each side) for the vacuum pumping system. Additional passthroughs are provided on the wall adjacent to the loop enclosure of the fixed head and on the closed end of the retractable chamber section for the liquid-metal piping, instrumentation, and power leads. Figure 21 shows the retracted section with an instrumented-model potassium radiator in position.

The chamber is of double-shell construction except for a 3-inch-thick endplate at the fixed head. The internal shell is made from 1/4-inch-thick, type 304 stainless-steel plate. The external shell is of 1/4-inch carbon steel. The 3-inch endplate is also made of carbon steel with a stainless-steel cladding on the interior surface of the tank. The entire interior surface area of the vacuum chamber is type 304 stainless steel, selected because of its favorable outgassing characteristics at high vacuums. All the passthroughs were stainless steel seal-welded to the inside chamber surface.

The internal surface of the chamber was given a number 4 grit blast finish and was painted with an organic base black paint (missile black - MIL-E-10687B). This paint, when applied to stainless steel, has a total hemispherical absorptance of 0.93 and 0.91 for incident radiation from source temperature of 1200° F and 1600° F, respectively. Samples of this painted blast surface finish were evaluated against a correspondingly painted satin finish and a painted as-received finish and were found to have superior outgassing characteristics.

The vacuum pumping system used in the installation (fig. 22) was designed to reduce the vacuum chamber pressure to  $10^{-3}$  millimeter of mercury. This pressure was con-

sidered low enough to reduce the convective heat transfer to a negligible amount. The system consists of three types of rotary mechanical pumps connected in series and connected to the vacuum chamber by a 12-inch-diameter pipe through a 32-inch flange. A roughing pump, which has a pumping speed of 250 cubic feet per minute, reduces the chamber pressure to 10 millimeters of mercury. A booster pump, which has a speed of 840 cubic feet per minute, is connected ahead of the roughing pump and operates in the pressure range below 10 millimeters of mercury. A forepump (second-stage boost pump), which has a pumping speed of 3435 cubic feet per minute, is located ahead of the booster pump and operates in the pressure range below 5 millimeters of mercury. Both the booster-forepumps are two-lobe-type rotary pumps that operate dry and will not leak or backstream oil upon shutdown. Vacuum-chamber pressure is measured by a thermocouple type gage with pressure readout in the control room. The 32-inch flanges on the fixed head were specified for future application of diffusion pumps to permit operation down to a  $10^{-7}$  millimeter of mercury pressure environment.

A cooling oil, which was compatible with molten potassium and sodium, for maintaining a fixed temperature value on the chamber inner surface, is circulated between the inner and outer shells. This oil is also used for cooling the radiator supports and radiation shields, which protect both the 3-inch endplate and the 32-inch flanges.

The oil-cooling system, shown schematically in figure 23, was designed to maintain the chamber wall at temperatures below  $150^{\circ}$  F with all surface temperatures maintained within a variation of  $25^{\circ}$  F. The oil system also provides the coolant for the vacuum pumps and the test-loop vapor traps (also shown in the figure). Basically, the oil system consists of two pumps: one for the vapor traps located within the test enclosure and one for the vacuum chamber and vacuum pumps. Each pump has a water-cooled heat exchanger. A throttling valve is used to vary the vacuum chamber oil flow rate up to 175 gallons per minute at a temperature of  $100^{\circ}$  F. The oil flow rate is measured by a positive displacement flowmeter. The temperature of the oil was controlled by varying the water flow rate through the water-cooled heat exchanger.

## Loop Pressurization and Vacuum Purging Systems

A vacuum system with a 13-cubic-foot-per-minute mechanical vacuum pump is used to purge ambient gas (air) from the loops, to outgas the loops prior to filling with liquid metal, and to operate the vapor loop at subatmospheric pressure conditions. Argon gas is used to assist in the loop purging operation, to establish the operating pressures of the individual loops, and to transfer liquid metal between containers. Figure 24 gives a schematic diagram of the vacuum and argon systems.

In this system, the vacuum pump is connected to a 2-inch-diameter vacuum manifold, which in turn is connected to the sump tanks and sample station. Vapor traps are provided at each sump tank to prevent liquid vapors from being pulled through the vacuum pump. The vacuum manifold is also connected to the pressure vents of the vapor loop to provide a subatmospheric sink pressure for the loop. To purge the entire system, prior to charging with liquid metal, the vacuum pump evacuates each loop to  $10^{-2}$  millimeter of mercury. The lines in the vapor loop are equipped with heaters to prevent vapors from freezing and causing a plug in the lines. During the purging process purified argon gas is bled back into the loop to dilute the contaminants in the loop. Repetition of this process achieves a very low level of impurities without resorting to a high vacuum. Once the loops have been purged, they are maintained at 10 pounds per square inch gage.

The argon supply for pressurizing the loops (fig. 24) is maintained by a bank of high-pressure gas bottles containing a total of 52 000 standard cubic feet of commercially purified argon. A gas pressure regulator adjustable from 0 to 200 pounds per square inch gage reduces this supply to the desired operating range (120 to 150 psig). The argon is purified by an inline gas purification system, which reduces the total impurity level to less than 1 part per million each of oxygen, nitrogen, carbon dioxide, and water vapor. Argon is supplied to the high point (expansion tank) and to the sump tank of each loop through individual pressure regulators which are controlled from the control room. Since all the pressure regulators are nonrelieving, vent valves, which are also operated from the control room, relieve argon pressure from the expansion and sump tanks of each loop. The pressure vents of the heater loop and the cooler loop vent directly into the atmospheric exhaust system. A pressure equalizing line is connected between the high point and the sump tank of each loop. When a valve in this line is opened, the pressure in the entire loop including the sump tank is equalized. This provides a means of gravity dumping either hot or cold liquid metal back into the sump tanks without venting.

Argon is also available at the liquid-metal sample station for purging the sample tube before taking a sample and at the filling stations for assisting in the transfer of liquid metal between containers.

## Instrumentation

Liquid level. - The liquid level in each tank of the three liquid-metal loops is measured by a continuous level-indicating system. This system was designed to measure the change in resistance of a fixed metallic probe located in the tank, where this change in resistance can be expressed as a measure of the liquid level. The probe was made in the shape of the letter J and installed vertically from the top of the tank. The range of level to be measured traverses the short leg of the J. A schematic drawing of the probe and



its equivalent electrical circuit is shown in figure 25.

The probe assembly contains two stainless-steel leads swaged into a stainless-steel tube which serves as the outer sheath. All three elements, the two leads and the outer sheath, are electrically insulated from each other by a metallic oxide except at the tip of the short leg of the J where they are welded together. During operation, a constant voltage is applied to one of the leads through a connector installed on the open end of the probe outside the tank. A current (dc) is caused to flow through this lead to the welded tip and down the outer side of the sheath to a point at the level of the liquid where it enters the liquid metal. The liquid metal shorts out the rest of the probe and provides a direct path to the tank walls and to ground. The voltage developed across the length of the short leg of the probe, which protrudes above the liquid surface, is proportional to the liquid level. This voltage to ground is measured by a high-impedance meter ( $10^7 \Omega$ ), which uses the other lead wire in the probe. The constant voltage across the probe is maintained by a feedback-type voltage regulator in the power supply. Since the resistance of the probe is temperature sensitive, the lead from the feedback circuit is connected to the current-carrying lead of the probe (point C, fig. 25). Since all the current lead from point C to the tip of the probe was inside the tank, it was exposed to the same temperature gradient as the probe sheath. Constant voltage is maintain from point C to point G (ground).

The relation that defines the alkali liquid-metal level in terms of a linear resistor is derived from the electrical circuit diagram shown in figure 25. The theory of operation is as follows:

$$V_{CG} = I(R_w + Xr + R_M) \quad (20a)$$

and

$$V_{AG} = I(R_M + Xr) \quad (20b)$$

where

$V_{CG}$  constant regulated supply voltage, V

$I$  current through probe, A

$R_w$  resistance of stainless-steel current-carrying lead from point A to point C,  $\Omega$

$X$  length of probe sheath above liquid-metal surface, in.

$r$  resistance per unit length,  $\Omega/\text{in.}$

$R_M$  resistance of liquid metal and container,  $\Omega$

$V_{AG}$  probe output voltage, V

The indicator and feedback circuits are very high impedance circuits and draw negligible current. Therefore, since

$$R_M \ll Xr \ll R_w$$

then

$$\frac{V_{AG}}{V_{CG}} = \frac{R_M + Xr}{R_w + Xr + R_M} \approx \frac{Xr}{R_w} \quad (21)$$

Furthermore, since  $r$  and  $R_w$  have the same temperature coefficient,  $r/R_w$  is a constant independent of temperature. Therefore,

$$V_{AG} = \frac{V_{CG}}{R_w} Xr = kX \quad (22)$$

or

$$X = \frac{V_{AG}}{k} \quad (23)$$

where  $k$  is a constant independent of temperature. This constant was evaluated by shunting known lengths of probe from the free tip before installation. After installation, the operating current was set the same as the calibration current. The probe was installed in the tank with the bottom of the J about 1/2-inch above the bottom tank surface. The height of the probe tip above the tank bottom was measured before the final welding operation. The liquid level above tank bottom is then defined by

$$H = D - X \quad (24)$$

where  $H$  is the liquid level above the tank bottom in inches and  $D$  is the height of the probe tip above the tank bottom in inches. Liquid levels below the probe bottom and above the probe tip cannot be measured.

Flowmeters. - The electromagnetic flowmeters used for measuring liquid-metal flow rate operate on the same principle as a direct-current generator. A photograph of an installed flowmeter is shown in figure 26. The pole faces of a horseshoe-type permanent magnet are diametrically opposed on the pipe through which the liquid metal flows.

Two wire-terminals are attached to the liquid-metal pipe at opposite points of the diameter perpendicular to the magnetic flux. With the liquid-metal flow acting as a moving conductor, the flowmeter becomes a direct-current generator that induces a voltage at the terminals.

The principle of flow measurement is based on the rule for three mutually perpendicular vectors: flux, current flow, and velocity of a conductor. Liquid-metal flow rates can be calculated from the basic direct current generator equation:

$$E = BvL \times 10^{-8} \quad (25)$$

where

**E** generated electromotive force, V

**B** flux density, G

**v** velocity of conductor fluid, cm/sec

**L** length of conductor in magnetic fluid, cm

Rearranging equation (25), adjusting the units, and substituting the inside diameter *d* of the fluid-carrying conduit for the length of conductor in the magnetic field yield the basic flow equation in terms of flow rate in gallons per minute:

$$Q = \frac{d \times 10^4}{3.18B} E \quad (26)$$

where

**Q** liquid metal flow, gal/min

**d** inside diameter of conduit, in.

**B** flux density, G

**E** generated electromotive force, mV

Since the wall of the fluid-carrying conduit is also a conductor and provides a parallel path for the current created by the generated voltage, a correction factor **K** is necessary for the generated voltage caused by this shunting effect:

$$K = \frac{2 d/D}{1 + (d/D)^2 + (r_f/r_w) [1 - (d/D)^2]} \quad (27)$$

where

K correction factor

d pipe inside diameter

D pipe outside diameter

$r_f$  electrical resistivity of fluid

$r_w$  electrical resistivity of pipe wall

There are other effects that can change the sensitivity of the meter, such as magnetic end effects, magnetic and terminal alignment, and temperature. However, conditions inducing these effects were avoided by careful design and installation. For example, end effects of the flux field were minimized by making the pole faces at least four pipe diameters long. Careful alignment of the magnet with respect to the terminals during installation minimized cosine errors. These and other precautions are discussed more thoroughly in reference 5. In the installation of the flowmeters, the ratio of the magnetic-pole-face length to the conduit inside diameter was greater than 4. The temperature of the magnet pole faces did not change appreciably to warrant a temperature correction. Therefore, the final equation used for calculating the liquid-metal flow rate is

$$Q = \frac{d \times 10^4}{3.18 B K} \frac{E}{K} \quad (28)$$

The output voltage of the flowmeter was read on a continuous recording and indicating potentiometer-type instrument located in the control room.

Pressure measurement. - Conventional Bourdon tube pressure gages are used to measure the loop cover gas pressures and auxiliary service gas pressure. These gages are located in the control room and at the test cell.

A volumetric type sensing system is used for measuring liquid-metal pressures at high temperatures in the potassium test loop. The pressure sensing element consists of a chamber that is divided by a flexible metallic diaphragm. One side of the diaphragm is exposed to the hot liquid metal, while the other side is connected to a Bourdon tube through a length of capillary tubing filled with NaK. Since the NaK is trapped between the diaphragm and the Bourdon tube, any motion of the diaphragm caused by a change in pressure of the pipe side is transmitted to the Bourdon tube through the NaK. The deflection of the Bourdon tube is measured by a linear variable-differential transformer. This signal is directly proportional to the pressure and is continuously monitored on a milliammeter located in the control room.

Temperature measurement. - System, alarm, and control temperatures are meas-

ured with surface-mounted open-junction Chromel-Alumel alloy thermocouples. Figure 27 shows a typical thermocouple installed on a section of facility piping with the insulation parted to expose the thermocouple. Small stainless bands are spotwelded over the thermocouple to hold it firmly in position. The alloy wire near the junction is looped generously to provide for thermal expansion.

Temperature readout instrumentation consists of continuous recording potentiometer instruments and single-point indicating potentiometers with selector switches. In order to reduce costs, copper lead wire was substituted for alloy wire to extend the thermocouple leads from the facility terminal strips to the control room selector switches. For accurate reading, this procedure requires that all copper-to-alloy junctions be at the same temperature. Under these conditions, only one pair of interconnecting alloy leads that connect to the temperature readout instrument was necessary. Accordingly, all the alloy leads from the thermocouple were terminated in a junction box that is maintained at uniform temperature by an air blower. The copper extension leads were used between this junction box and the thermocouple selector switch in the control room. Copper leads were also used from the common terminals of the selector switches to transmit the selected thermocouple signal back to the junction box. In the junction box, the copper leads were connected to alloy leads to form a compensating thermocouple junction. The alloy leads then transmit the signal directly to the readout instrument.

## Control Room

The space radiator and condenser facility was designed to be completely operable from a remote control room, which contained all the system controls, instrumentation readouts, research data recorders, and smoke and malfunction annunciators. As shown in figure 28, the control panel is L-shaped about a large viewing window which overlooks the facility in the test cell. The control panels are constructed as a combination of a console control desk and an upright instrument display. The control console contains a graphic display of the loop piping with the switches and annunciator lights for the remotely operated valves spotted on the display. Pump, main heater, hot trap, and superheater controls are also located on the graphic display. The instruments and line-heater controls associated with one loop were grouped together above the graphic display of that loop. The annunciator alarm panel is located in the corner of the L. All the loop temperatures are read on indicating instruments with multipoint selector switches. Recording instruments were used for main heater and superheater wattmeters, flowmeters, and automatically controlled variables. Dual-trace recorders were used on the flowmeters to record both meter output and meter temperature because the relation between meter output and liquid-metal weight flow was temperature sensitive. Recording instruments

were used on the automatically controlled variables mainly for tuning the control.

All the overtemperature, overpressure, and malfunction alarms, except those of the main heater, triggered the annunciator panel but did not automatically shut down any equipment or operate any valves. The main heater, however, was automatically deenergized by either overtemperature or loss of heating fluid flow signals.

. Lewis Research Center,  
National Aeronautics and Space Administration,  
Cleveland, Ohio, November 18, 1966,  
120-27-04-36-22.

## APPENDIX - SPECIFICATIONS FOR SPACE RADIATOR AND CONDENSER FACILITY

This section contains the technical sections of the government specifications for the space radiator and condenser facility. A supplemental exhibit A is also included. It contains minor changes and clarifications to the original specifications. The bidders were to submit three alternative plans in their proposals. These alternatives with the Government's priority of interest are outlined in the following table:

Alternative	Description	Government priority
I	Vapor condensing by convective condenser using liquid-metal cooling loop	Third
II	Alternative I plus the vacuum chamber with alkali-metal vapor and coolant lines to it	Second
III	Alternative II plus an independent auxiliary heating loop for liquid alkali metal to the vacuum chamber	First

The contract for the facility was negotiated on alternative II. The preceding specifications are the original ones submitted for the bid and do not include the contractor's negotiated exceptions, which were generally minor in scope.

UNITED STATES  
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION  
LEWIS RESEARCH CENTER  
21000 BROOKPARK ROAD  
CLEVELAND 35, OHIO

SPECIFICATIONS  
FOR  
SPACE RADIATOR AND CONDENSER RESEARCH FACILITY

SPECIFICATION NO. C-26265

APRIL 28, 1961

SECTION I - DESCRIPTION, SCOPE, ETC.

1-01. Description:

This specification is for the design, fabrication, delivery, complete installation and initial operation and checkout of a complete high temperature liquid metal system for experimental research on heat rejection radiators and condensers in a simulated space environment. System to be installed in Cell W-2A, Engine Research Building, located at the Lewis Research Center, National Aeronautics and Space Administration, 21000 Brookpark Road, Cleveland 35, Ohio.

1-02. Scope:

- (a) A complete recirculating liquid metal system is to be provided for the study of waste heat rejection components used in space Rankine cycle energy conversion units.
- (1) The facility will provide for two means of heat rejection; (1) direct condensation of vapor in a 2-phase multitube radiator enclosed in a vacuum chamber and (2) indirect condensation of vapor in a multitube compact condenser of the heat exchanger or spray type in conjunction with a liquid metal coolant circuit.
  - (2) Two test sections will be provided by the Government for assembly of the complete system. One test section will be designed for radiation type heat rejection and one will be designed for convection type heat rejection.
  - (3) The working fluid in the test sections is potassium. Heat shall be supplied to the test fluid from a separate liquid metal circuit by liquid metal as the heating medium. The liquid metal coolant circuit used in conjunction with the multitube condenser shall be compatible for use with sodium, NaK or potassium.



- (4) The coolant circuit shall have independent control of coolant flow rate and temperature drop. Provision shall also be made for the use of a single phase liquid radiator in a vacuum chamber as the condenser coolant circuit. Hereinafter in this specification the working fluid for the primary heating circuit and the condenser coolant circuit will be considered to be NaK.
- (b) The Contractor shall supply a complete package system, exclusive of the test radiator and condenser, but including the process system instrumentation and controls, electrical heating systems, electric power interconnect panels, liquid metal oxide and trace metal removal systems, inerting and cover gas systems, cover gas purification system, pressurizing and evacuating systems, safety systems, venting systems, insulation, trace heaters and enclosures with the exceptions indicated below. The Contractor shall install the system in the test cell and install the controls in the existing control room. The Contractor shall furnish the framework and control panel made up of 19 inch wide sub-panels. The Contractor shall make all connections to the interconnect panel, continue all lines to the control panel in the control room and to the electric power and other service sources. The Government will supply the cover gas and the test cell ventilation.
- (c) The Contractor shall furnish as part of the technical proposal and bid all schematic sketches, drawings, calculations, and other necessary information in sufficient detail to understand and evaluate fully both the complete system and components designs. Within 60 calendar days after award of contract, the Contractor shall furnish preliminary drawings, calculations to certify a 3:1 safety factor, heat transfer, and other necessary information to completely describe the system. (Drawings shall be checked and approved in the same manner as provided under Section 3-26 (a)).

1-03. Performance Requirements:

- (a) The system must meet all performance requirements in this specification. If the Contractor is unable to attain performance over the complete range of each parameter specified, then for each parameter the maximum range that will be attained shall be submitted.
- (b) After the system is delivered and the Contractor completes the installation, the Contractor shall provide the Government with detailed start-up, operation (normal and emergency), and shut-down instructions (5 copies), the potassium, the NaK, and the necessary equipment for a performance test of the system. The above equipment and information shall become the property of the Government. The Contractor shall also supply the personnel to cycle the system three times from ambient temperature to the following condition:

## SECTION I

Primary Heater maximum temperature - 1800° F.  
Condenser or Radiator Inlet Test Fluid temperature - 1600° F.  
Condenser or Radiator Inlet Test Fluid pressure - saturated vapor pressure at 1600° F.  
Condenser or Radiator Inlet Test Fluid vapor quality - 75 percent to 100 percent  
Test Fluid Flow rate - 590 lb/hr  
Condenser or Radiator Outlet Test temperature - 1600° F. max. (saturated liquid)

- (c) The system shall be dumped after each of the operating cycles. On the last cycle, the system must operate continuously for 40 hours at 590 lb/hr, 100 percent quality potassium vapor at 1600° F. at condenser inlet before acceptance by the Government. To be acceptable no modification or repair shall be required during the three performance test cycles. The Contractor shall, at the job site and at his own expense, make any repairs or modifications to complete the performance tests.

### 1-04. Delivery, Unloading, and Labeling of Components:

- (a) The unit shall be shipped as near a complete packaged system as possible, except for the items stated in (e) below. The package shall be shored and supported so that none of the components will be damaged during shipment or unloading. Suitable lifting lugs and skids shall be provided by the Contractor for any movement of the package.
- (b) All components, shall be supplied with metal tags showing design temperature, design pressure, flow capacity, contract number, drawing number and name of item. The tags shall be attached by chain or wire and be visible outside of the insulation.
- (c) The Contractor shall furnish to the Government, in the final set of drawings, information showing size, weight, lifting lug and/or skid locations, etc; of the package.
- (d) The package shall be so designed that it can be moved easily through halls and buildings.

Cell door size - 10' 0" x 9' 11-1/2" high  
Hall width - 20' 6-1/2"  
Hall ceiling - 9' 10"

- (e) All gages, instruments, and other control panel mounted equipment are to be

furnished and installed by the Contractor. The vacuum chamber associated with the system may be shipped as a separate package, subject to conditions outlined in 1-04(a) above.

1-05. Drawings and Information Required from Contractor:

- (a) The Contractor shall submit for approval, within 120 days specified after award of contract, complete final drawings, including electrical drawings, control panel layout showing all items clearly labeled and graphic panel display, showing all dimensions, materials and pertinent information required for the installation of the system.
- (b) The Contractor shall also submit the following items to the Contracting Officer for approval:
  - (1) Layout of system in the test cell including vacuum chamber, and roof alternations for weather proofing of air intake and exhaust ducts.
  - (2) Complete wiring diagrams and control system drawings.
  - (3) Installation sketches of all monitoring and recording instruments.
  - (4) Performance data, characteristic curves for all equipment.
  - (5) Certified shop test and inspection reports as required by ASME Boiler Construction Code, however, Code stamp not required.
  - (6) Complete information such as Model No., Working Pressure, Range, Type, etc. for each piece of equipment.
  - (7) Instruction manuals and spare parts list (5 copies). Parts list shall include identification symbols or parts numbers for all replaceable parts and assemblies. The instruction manuals shall be bound in durable covers.
  - (8) Complete cleaning, welding, vacuum checking and material inspection procedures.
- (c) All drawings and other material submitted for approval shall be submitted to the Contracting Officer and marked with the contract number, the title of the contract and the name of the Contractor. Five (5) copies of each item, accompanied by a letter of transmittal in quadruplicate, listing the submission, shall be submitted. One (1) copy of each item submitted will be returned to the Contractor by the Government, approved or marked to indicate the corrections required. Nine (9) copies of each corrected item or four (4) copies of each item approved without exception shall then be submitted to the Representative of the Contracting Officer with a letter of submittal in quadruplicate. One (1) copy of each corrected item showing final approval will be returned to the Contractor.
- (d) Contractor's drawings returned marked as indicated above and data approved shall not be construed as a complete check, but will indicate that the general design and proposed method of construction are satisfactory. This approval will not relieve the Contractor of his responsibility for the correctness of dimensions, for the proper design of details, for the proper functioning of the finished work in accordance with the contract requirements, or for furnishing any materials and/or work required by the contract which may not be indicated on the drawings when approved.

### SECTION III - TECHNICAL PROVISIONS

#### 3-01. General Objectives:

- (a) The research objectives are to study the heat transfer and internal flow processes of liquid potassium Rankine cycle waste heat rejection components. Several types of heat rejection systems are to be studied.
  - (1) Radiation Condenser: This device condenses all the vapor from the fluid discharged by a turbine (or quality control device). It rejects the heat of condensation by radiating to a heat sink. The heat sink in this research program will be the walls of a vacuum tank.
  - (2) Convective Condenser: This device also condenses the turbine (or quality control device) discharge fluid, but transfers the heat of condensation by convection to a liquid metal coolant. This coolant fluid then rejects heat in either a radiator or another convective heat exchanger which employs air cooling. The secondary fluid may be either potassium, sodium, or NaK.
  - (3) Jet-Spray Condensers (Future): This device condenses the turbine (or quality control device) discharge vapor by physically mixing it with a high velocity stream or streams of subcooled liquid. The heat of condensation is then carried away in the coolant fluid. The coolant fluid must be potassium.
  - (4) The devices listed in 3-01(a-1), (a-2) and (a-3) are research items and are not to be considered a part of this contract.
- (b) In addition to the above, it is required that the facility have the capability of permitting operation with a turbine or turbine simulator (nozzle), if desired at a later date.

#### 3-02. Research Requirements:

The facility shall provide potassium vapor to the research test sections in a state of temperature, pressure, and vapor fraction similar to that of turbine discharge in a Rankine cycle. In addition, the facility shall be designed to be capable of providing potassium vapor to a research turbine (or simulating nozzle) upstream of the research condensers at temperatures up to 1800°F. and at a maximum pressure corresponding to saturation pressure at 1725°F. The facility shall also return the potassium from the test sections to its heat source and prepare it for recirculation. The system shall also provide two heat sinks, one for radiation and another for convection.

3-03. Range of Operation:

The following is a list of ranges over which the facility shall satisfactorily operate. The various independent parameters shall be controllable, measurable, variable, and reproducible over the entire range.

- (1) State of potassium entering the condenser test section:  
Pressure: 8 psia to saturated vapor pressure at 1600°F. ( $\pm 1\%$ )  
Temperature: 1300°F. to 1600°F. ( $\pm 1/2\%$ )  
Vapor Quality: 75% to 100% (The minimum acceptable means of measuring inlet vapor quality will be by system heat balance calculations.)
- (2) Flow rate of potassium:  
59 lb/hr to 590 lb/hr.  $\pm 2\%$
- (3) Heat rejection range from test sections: (Latent heat +200°F. of sub-cooling)  
15 KW to 150 KW

3-04. Design Considerations:

- (a) The system and all components shall be designed for 10,000 hrs. of cyclic operation. Each cycle will consist of approximately 200 hrs.
- (b) All piping and other components of the system shall be designed with a 3 to 1 safety factor based on the stress to rupture or short time yield curves whichever is lower, considering thermal expansion, weight and pressure combinations over the whole range of operating temperatures and pressures.
- (c) The choice of materials for the system shall be the responsibility of the Contractor but the type of material proposed shall be approved by the Representative of the Contracting Officer prior to any fabrication of the system.
- (d) Seamless pipe or tubing shall be used throughout the system. This plumbing shall be capable of maintaining its structural strength and resist rupture at the maximum operating temperature and pressure under continuous service. All pipe joints shall be welded. Piping shall have suitable supports, anchors and thermal expansion provisions.
- (e) All welding shall conform to Lewis Research Center specification LRC-1 dated January 20, 1961.
  - (1) Welding with 100% radiographic inspection, of the material in contact with liquid metals shall conform to Class 1 of the

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Reference Specification. Should the material not be listed in the specification, the Contractor shall submit to the Government for approval the complete welding procedure for that material.

- (2) Welding of steel structures, supports, etc., shall conform to Class III of the reference specification.
- (f) The test fluid boiler, superheater, quality control device, convective condenser, radiation condenser and the flow lines connecting these components shall be so designed to minimize the effect of gravity on the flow of potassium through the system. A horizontal attitude will be utilized in the design of the convective and radiation condensers by the Government with provisions for slight inclination for natural drainage to sump tanks. This approach shall be employed by the Contractor in the design of the remaining aforementioned items. The maximum flow velocity in any vapor line shall not exceed 200 feet per second.
- (g) The Contractor shall provide complete detailed wiring diagrams showing all connections to be made for the electrical, instrument, control and safety shutdown systems.
- (h) All pipe and components in the system shall be traced with line heaters with monitoring thermocouples. This tracer system shall be divided into several circuits. The heaters shall have sufficient capacity to heat the pipe and components to 250°F in 6 hours when the system is filled.
- (i) All instruments, gages, and controls on the control panel supplied by the Contractor shall be flush mounting. Instrument lines shall be separated by a minimum of three feet from power lines and control lines and shall be shielded.
- (j) Before shipment each component of subassembly shall be assembled and pressure checked. After delivery and final assembly, the complete system less the vacuum chamber shall be pressure checked and also leak checked, using helium, with a mass spectrometer. The mass spectrometer will be provided at the assembly site by the Government. With the system at 50 microns absolute pressure (.000967 psia) the pressure rise in the system shall not exceed 5 microns in 4 hours with the vacuum pump disconnected.
- (k) Consideration shall be given to minimizing thermal stress problems during startup and steady-state operations.
- (l) Provision shall be made in the design to permit access to the interior of the various systems so that they can be cleaned internally. For example, when a change from NaK to potassium is made, the residual NaK and its oxides will have to be cleaned from the interior surfaces to avoid contamination of the potassium. The Contractor shall submit to the Government for approval their cleaning specifications for all materials in contact with potassium, NaK and sodium.

- (m) All mechanical work and equipment shall be designed, constructed, and installed in accordance with the best present day manufacturing practices and shall conform to and be tested in accordance with applicable sections of the latest revisions of the following codes and standards unless specified otherwise.
- (1) American Society of Mechanical Engineers (ASME)
  - (2) American Society for Testing Materials (ASTM)
  - (3) American Standards Association (ASA)
  - (4) American Welding Society (AWS)
  - (5) American Institute of Steel Construction (AISC)
  - (6) National Association of Fan Manufacturers (NAFM)

3-05. Heaters:

- (a) The system shall be designed such that the test fluid shall be heated in a boiler which utilizes a liquid metal heat supply loop. The liquid metal shall be heated by means of a forced convection, electric powered heater rated at a power output necessary to reject 150 KW at the test condensers. The liquid metal shall remain in the liquid state in the heat supply loop up to a maximum temperature of 1800°F. entering the test fluid boiler. Suitable means shall be provided for pressurizing this loop with argon gas. The choice of liquid metal used in the heat supply loop is left to the Contractor.
- (b) A separate auxiliary liquid metal heater shall be supplied for the purpose of independently supplying liquid metal at temperatures from 1300°F. to 1600°F. and pressures necessary to maintain liquid under all conditions, to an all-liquid radiator in the vacuum chamber. This heater shall be preferably electric powered and rated at a power output sufficient to produce a 50 KW heat rejection in the test radiator.

3-06. Boiler:

The test fluid shall be heated and vaporized by means of a liquid-metal heated, counter flow, forced convection, type heater exchanger. The heating liquid shall flow in the outer passage and transfer heat to the inner passages and test fluid by forced turbulent convective heat transfer. All portions of all the liquid metal loops operating above 1650°F. shall be constructed of high temperature "super-alloys"; however, use of high temperature materials throughout the rig shall be kept to a minimum.

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#### 3-07. Superheater:

The discharge from the boiler shall be passed through a superheater designed to provide a temperature margin and a completely dry state of the potassium before it enters the quality control device. The superheater shall provide 0 to 75 Fahrenheit degrees of superheat over the range of operating temperatures and may be electrically powered.

#### 3-08. Quality Control Device:

For each saturation temperature and weight flow rate combination it is desired to be able to vary the quality of the test fluid entering the test section (or turbine) over the entire range from 75% to 100%. In order to accomplish this requirement, devices such as liquid-vapor separators, throttles, pre-condensers and liquid-vapor mixers may be employed along with the control of the test fluid boiler and superheater. If the Contractor cannot provide quality control over the entire range as specified, then the range or combinations of parameters which the Contractor will attain shall be submitted. Complete instrumentation shall be provided for determination of the temperature and pressure of the potassium vapor leaving the quality control device. Determination of vapor quality will be as specified in 3-03(1).

#### 3-09. Throttling Devices:

Throttling devices may be needed in the vapor generation system to provide control of the pressure level and flow rate (in addition to the pump control) and for stability requirements. Combinations of fixed and variable throttling devices may be used. The design shall be such as to facilitate removal and replacement of the throttling devices. Together with the test fluid pump and condensers and the pressurizing (or, in some runs, vacuum) system the throttling devices shall be capable of providing stable operation over the required range. All valves used as throttling devices shall be operated remotely from the control panel with indicating lights to show the full open and full closed positions. The valve body shall contain a thermocouple to indicate its temperature before operation. The thermocouple leads shall terminate at the disconnect panel.

#### 3-10. Liquid Coolers:

- (a) The test convective condenser coolant flow loop requires an additional heat exchanger for removal of the heat acquired by the convective condenser in condensing the potassium vapor and subcooling the condensate. The cooler shall be of sufficient capacity to remove the latent heat of condensation and sufficient heat for 200°F. of subcooling under all test conditions. The cooler shall be capable of liquid metal coolant temperature drops ranging from 100°F. to 400°F. at 150 KW power level.



- (b) For protection of the liquid metal pumps in the test fluid loop, the primary heating loop and the auxiliary heating loop, a liquid cooler shall be provided upstream of these pumps and shall have sufficient capacity to cool the liquid metals by 200°F. at maximum flow rate.
- (c) The coolers as specified in 3-10(a) and 3-10(b) above shall be cooled by ambient air at 80°F. The cooling air exit temperature shall not exceed 600°F. under any conditions. The Contractor shall supply all necessary duct work or piping inside and outside the protective enclosure as well as external or internal blowers or pumps and cooling air control valves.
- (d) The coolers shall be fabricated from alloy materials of sufficient thickness to allow continuous operation at maximum conditions. The design shall allow for thermal expansion differentials resulting from cooling air failure on heat-up or cool-down conditions.
- (e) The Contractor shall supply thermocouples to measure the inlet and exit cooling air temperatures and liquid metal inlet and exit temperatures on all liquid coolers. A temperature corrected flow meter and liquid metal detector shall be provided by the Contractor in all cooling air outlet ducts.
- (f) The liquid metals in the condenser coolant loop shall remain in the liquid state up to the maximum temperature of 1500°F. (leaving the test condenser). Suitable means shall be provided by the Contractor for pressurizing this loop with argon gas.

3-11. Flowmeters:

Flowmeters shall be supplied in all liquid metal loops for the purpose of measuring the various liquid metal flow rates. The flowmeters shall be the magnetic force type giving a voltage signal proportional to the flow rate and shall have calrod heaters for preheating purposes. All flowmeters shall be accurate within 98% at all flows. All flowmeters shall be supplied with calibration curves. Each flowmeter shall be wired to the disconnect panel with voltage output leads and a thermocouple lead to show tube temperature of the flowmeter.

3-12. Pumps:

The liquid metal pumps shall be electromagnetic, alternating current induction type or direct current conduction type pumps. The pumps shall be supplied with adjustable autotransformers and capacitors for power factor corrections or magnetic amplifiers for control of pump output. All controllers for varying the pump output shall be located in the control room and shall be flush mounted in the control panel. Thermocouples shall be provided for each pump with relays for automatic shut-down of each pump if its maximum operating temperature is exceeded. All pumps shall be capable of continuous

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operation with an inlet temperature of 1500°F. Each pump shall have its own calrod heating element for preheating purposes. The test fluid pump shall provide a variable flow over a range adequate to provide the specified test section flows. In addition to the test fluid pump, necessary pumps shall be provided in the liquid cooler loop, heat supply loop and auxiliary heating loop and shall have variable flow range adequate to provide the necessary flows in the specified loops.

#### 3-13. Sump Tanks:

- (a) Each liquid metal loop shall be provided with a sump tank which shall have a capacity equal to twice the capacity of the remainder of respective loops.
- (b) Each tank shall be equipped with electric heaters to maintain the various liquid metals in the liquid state and at a temperature 25°F. to 50°F. above the melting point. The tanks shall be equipped with the necessary fill line and valve which will maintain a tight vacuum on the tank once the loop is filled. The tanks shall be provided with the necessary emergency vent valve and lines for cover gas and vacuum. Continuous liquid level indication shall be provided between 25% and 90% of the full volume. All tanks shall be designed for the maximum system working pressure and shall be insulated to provide a maximum outside surface temperature of 140°F.
- (c) The Contractor shall furnish a suitable heater for melting the various liquid metals within the supply drums and means of transferring the liquid metals from the supply drums to the sump tanks.

#### 3-14. Dump Valves:

- (a) Each sump tank shall be provided with a dump valve of sufficient size to dump the complete liquid metal loop in 3 minutes or less at all operating conditions. The dump valve shall be a normally open valve and shall be operated remotely from the control panel in the control room. The valve position shall be indicated either full closed or full open by indicating lights on the control panel. The valve shall be equipped with a thermocouple on the body to indicate its temperature before it is operated. The valve shall be operated by a pneumatic control valve utilizing a separate pressure supply than the system pilot pressure supply.
- (b) The Contractor shall supply and install the temperature indicating gages, pneumatic pressure supply, and valve operators.

#### 3-15. Expansion Tanks:

Any expansion tank required by any fluid system shall be equipped with electric heaters to maintain the liquid metals 25°F. to 50°F. above their

melting points and shall have a volume equal to the capacity of the rest of the respective loop, exclusive of the sump tank. The expansion tanks shall have a liquid level indicator at the 75% capacity level (excepting test fluid loop expansion tank) and a liquid level indicating gage in the control room. The test fluid loop expansion tank shall have continuous liquid level sensing and gage indication from 0% to 75% capacity. The tanks shall be designed to withstand full vacuum as well as the maximum working pressure. The test fluid loop expansion tanks shall be so designed to minimize the contribution of a gravity pressure head to the system as the liquid level rises in the expansion tank.

3-16. Vacuum Chamber:

- (a) The air cooled vacuum chamber is intended to act as a heat sink for the radiant heat rejection from the liquid metal system and also to simulate a space environment.
- (b) The inside surface of the vacuum chamber shall be coated or treated to achieve the highest value of thermal emissivity possible for absorption of heat from the test radiator. Any coating or treatment shall be subject to approval by the Contracting Officer.
- (c) The vacuum chamber shall be designed to be capable of maintaining a pressure of  $1 \times 10^{-7}$  mm of mercury under all operating conditions and with the surface coating or treatment completed. To demonstrate this, the Contractor shall evacuate the chamber to  $1 \times 10^{-3}$  mm Hg (1 micron) and leak check with a mass spectrometer using helium on the outside of the chamber. The maximum permissible leak rate into the chamber shall be .01 micron-ft<sup>3</sup>/hr or  $1.04 \times 10^{-7}$  Std. cc/sec at a chamber pressure of  $1 \times 10^{-3}$  mm Hg, and ambient temperature and with the chamber isolated from the evacuating system.
- (d) The Contractor shall provide all necessary jacketing, ductwork and air supply for removing the heat absorbed by the chamber wall during all operating conditions. The chamber inner wall shall not exceed 150°F. on the cylindrical portion under all operating conditions. The Contractor shall supply thermocouples to indicate the inlet and exit coolant temperatures. The cooling air exit temperature shall not exceed 150°F. under all conditions. A temperature corrected flowmeter shall be provided in the cooling air outlet duct.
- (e) The vacuum chamber shall be 18 (eighteen) feet in length overall and 8 (eight) feet inside diameter. Access into the chamber shall be by means of a flanged joint at one end of the chamber and the full diameter of the chamber. This joint shall be fastened by quick-disconnect clamps rather than bolting. The main cylindrical section of the chamber shall be designed to be moved away from the fixed flanged end of the chamber on tracks mounted on the test cell floor. The test radiators will be mounted on the fixed end of the chamber and all fluid lines and instrument leads led into the test radiator through

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the fixed head or end. The fixed end is to be a flat head three (3) inches thick and full chamber diameter.

- (f) The Contractor shall furnish 4 (four) 32 inch and 2 (two) 4 inch flanged openings into the fixed end of the vacuum chamber for connection of high vacuum pumps by the Government at a future date. The flanged connections of these openings shall be as close to the chamber wall as possible to minimize vacuum line lengths.
- (g) All flanges shall be supplied with "O" rings fabricated from Parker Compound V271-7 or equal. All other seals shall be fabricated from materials that will not outgas into the test chamber.
- (h) The pressure pickup on the chamber shall be of the thermocouple type. Provision shall be made for the future installation of a Bayard-Alpert ionization gage. A Veeco combination thermocouple-ionization gage or approved equal with a range of 1 mm to  $2 \times 10^{-10}$  mm Hg shall be installed on the control panel in the control room.

#### 3-17. Vacuum Systems:

- (a) The vacuum system for the various liquid metal loops is required primarily to evacuate the loops as part of the inerting and purge system and for startup evacuation for sub-atmospheric test conditions. The system consists of the vacuum pump with a filter (or vapor trap) and a cold trap between the pump and the loops and a vacuum valve to shut off each loop and the inlet. The pump shall be capable of evacuating the system to  $10^{-2}$  mm Hg absolute pressure within 1 hour.
- (b) A separate vacuum system shall be provided for evacuating the vacuum chamber. The vacuum pump shall be capable of evacuating the chamber to a absolute pressure of  $10^{-3}$  mm of mercury within 1 hour. The system is required to evacuate the vacuum chamber to test conditions prior to operation and shall consist of the vacuum pump with a cold trap at the inlet and a vacuum valve to shut off the inlet.

#### 3-18. Liquid Sampling Devices:

- (a) The system shall be supplied with liquid sampling devices for removing metal samples from each loop for analysis of trace metals. The sample shall be approximately 25 cc. The sampling device system shall be designed for one man operation in the test cell while the system is operating at any condition of temperature, pressure and flow.
- (b) The sampling system shall be complete with cover gas, heaters, valves and any other necessary equipment. The devices shall be so designed that air cannot

enter the system while samples are being taken. The sampling station shall be external to the main enclosure, shall have all necessary controls for taking the sample, and shall be designed with the utmost safety consideration for protection of the operator taking the sample.

3-19. Oxide Control and Indicating Systems:

An oxide control and indicating system shall be supplied for each liquid metal loop and shall be supplied complete with economizer, magnetic flowmeter, cooler, blower, controller and air motor, damper, oxide indicator, hot trap, cold trap, manual control, flow-temperature recorders, and thermocouples. The Contractor shall make all necessary connections and install all control, recording and monitoring equipment in the control room. The system shall be capable of purifying the various liquid metals to a maximum of 20 parts per million oxide content after 90 minutes operation at 1500°F.

3-20. Pressure Pickup, Transmitters, Indicators and Recorders:

All pressure pickups and transmitters shall be supplied complete with direct indicating gages and recorded on a Bristol recorder or equal. All components shall be completely tested, supplied and installed in the control room by the Contractor. The pressure measuring system shall be accurate within  $\pm 1.0\%$  at full range.

3-21. Thermocouples:

- (a) The location of all thermocouples on the system (exclusive of the research condensers) shall be decided by the Contractor and shall be subject to approval by the Contracting Officer.
- (b) The installation of the thermocouple element shall be as shown on drawing CB-841559 (Section 1-02(d)). The choice of bare wire, but welded hot junction or insulated hot junction and thermocouple wire size is left to the Contractor and subject to the approval by the Representative of the Contracting Officer.

3-22. Safety:

- (a) The entire system (exclusive of the vacuum chamber) and the auxiliary heating loop shall be contained in protective fire proof enclosures which are designed to contain a spill and/or fire and to protect personnel and surrounding equipment from being sprayed or splashed with metallic liquids or vapor in case of failure of a pressurized line or component. Suitable quick removable (without bolting) access panels or doors shall be provided. The enclosures shall be vented at the top. In addition vent lines shall be provided for direct connection to relief valves or other pressure relieving or venting devices in the system. The air temperature within the enclosures shall not

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exceed 180°F. after 2 hours of operation. Means of cooling the enclosures shall be provided to meet this requirement. Any vent line emerging from the protective enclosures shall be provided with a liquid metal detector. Drain pans shall be provided to collect any liquid metal spill. The main drain pan shall include a number of easily removable smaller pans, covering the whole bottom area, which are no greater than two feet wide or four feet long. Each of these pans shall have an easily removable cover plate with an open area no greater than 35% to suffocate the burning liquid metal contained in the pans after a spill. Provision shall be made to allow overflow from any pan into an adjacent pan in the event of a major leak.

- (b) Careful consideration shall be given to provide a fail-safe feature for each component of the rig in the event of a power failure. Safety devices shall be provided with the system to protect all components from over-pressure or over-temperature conditions.
- (c) All components shall drain by gravity to sump tanks when the emergency dump valve is opened. Trouble lights shall be provided to indicate the cause for emergency shutdown. An audible signal shall be provided for indication of emergency conditions and shall have a manual switch to silence the horn. The system also shall have provision for indication when temperature and/or pressure is greater than maximum operating conditions to allow the operator time to take corrective measures before automatic shutdown results.
- (d) Use of any and all radioactive devices such as liquid level measuring components, etc., must have the approval of the Contracting Officer, therefore, complete information concerning such devices shall be submitted to the Government for evaluation.

#### 3-23. Cleaning and Painting:

All metal surfaces of structural or supporting equipment, accessory systems, other than stainless steel shall be cleaned and painted as follows:

- (1) All surfaces shall be free of oil, grease, dirt, rust and scale.
- (2) All surfaces shall be painted with two coats of O'Neil's #801 ready-mixed brushing silicone heat resisting aluminum paint, or equal.

#### 3-24. Electrical Provisions:

##### Design Requirements.

- (a) The following information is being furnished as a guide for the design, fabrication and installation of the electrical components of The Space Radiator and Condenser Facility.

The power available for the equipment at the Government site is rated at 440-volt, 3 phase, 60 cycles (maximum capacity 300 KVA).

- (b) The following electrical requirements are included as part of these specifications:
- (1) The Contractor shall furnish all transformers that are required to provide system voltages other than the voltage specified under paragraph 1.
  - (2) Heating elements shall be operated by means of magnetic contactors or relays.
  - (3) Blower motors or pumps shall be operated by means of magnetic starters.
  - (4) The power distribution panel, contactors, relays or starters shall be housed in a common NEMA Type 1 grouped control center enclosure similar to a motor control assembly. This assembly shall be prewired with the power feeders and control wires terminating on terminal strips in the enclosure for extension of these wires to the drive or heating equipment and the control or indication circuits to the remotely located control or operations panel.
  - (5) Thermocouple and instrumentation cables shall terminate in a terminal cabinet on a terminal strip for extension to the remotely located control or operation panel.
  - (6) Resistance wire heaters shall be of a high grade quality and shall provide quick heat when energized and rapid heat decay when de-energized; shall have a high temperature capacity with low heat loss, long life and shall be easy to install or service.
  - (7) Alarm circuits shall be of the automatic reset type.
  - (8) The control system, contactors, starters or relay coils, indicating lights, and electrically-operated indication or recording instruments shall be arranged for 120-volt operation.
  - (9) Push button stations, switches, and indicating lights shall be of the panel mounting type.
  - (10) The following control, indicating or operational items, shall be assembled on prewired panels with the wires terminating on terminal boards located at the rear of these panels, for extension of the wires to the operating or control unit. The width of these prewired panels shall be such so as to fit into the control panel structure.

- (aa) Preheat trace heater switches and indicating lights.
- (bb) Alarm devices, horn, indicating lights, and horn silence button.
- (cc) Instrument distribution panel.
- (dd) General control and indication.
- (11) Valves requiring indicating lights to show the open or closed positions shall be complete with limit switches.
- (12) Solenoid valves shall be rated at 120 volts.
- (13) Motors rated below 3/4 horsepower shall be rated at 120 volts single phase 60 cycles. Motor rated 3/4 horsepower and above shall be rated 220/440, 3 phase, 60 cycles and arranged for operation on a 440-volt system.
- (14) The trace heaters for the sump tank shall be arranged for automatic control so as to maintain a temperature rating not less than 250° or more than 350°F.
- (15) The design, manufacture and testing of the electrical equipment furnished under this contract shall conform to the standardization rules and requirements of the AIEE, the NEMA Standards as revised to date and shall meet the requirements of the National Electrical Fire Under Writers' Code and the National Electric Safety Code.

#### 4-25. Electric Installations:

##### (a) Materials.

The drawings and/or specifications for the installation of the Liquid Sodium Condenser and components shall be governed by the following:

- (1) Cables (power, control, instrumentation and thermocouples) shall be extended on cable trays (similar to Husky Products basket type) or conduit. Conduit shall be of a high grade galvanized white finish or shall be U.L. approved aluminum of prime 6063 alloy with 42 temp. Flexible conduit connections shall not exceed 12 inches if practical.
- (2) Exposed conduits shall run parallel to and at right angles with the lines of the building.
- (3) The electrical equipment shall be grounded to an existing ground loop.

##### (b) Electrical Workmanship:

- (a) All electrical work shall be installed in conformance with provisions as set



forth by the National Electric Code.

- (b) All circuits and equipment shall be tested for grounds, short circuits, continuity and proper operation. Any defects shall be corrected by the Contractor at his expense.
- (c) The Contractor shall obtain the approval of the Government before any work is performed requiring the shutting down of existing mechanical or electrical devices or services.
- (d) The Contractor shall obtain permission from the Government before cutting thru the walls. After all cutting operations and before completion of work these openings shall be sealed in a satisfactory manner.

4-26. Electrical Drawings and Instructions:

- (a) Electrical drawings submitted by the Contractor shall be easy to follow, of first quality workmanship, and of sufficient detail to enable the Government to review and check the drawings. Whenever applicable, devices shall be designated by American Standards Association Symbols and Function Numbers. Electrical diagrams shall be properly coordinated and cross-referenced to show interconnection between all devices and equipment. Each electrical device, conductor and terminal on all equipment shall have distinctive markings and shall correspond with similar markings on the connection diagrams.
- (b) The electrical diagrams shall include:
  - (1) One-line diagrams
  - (2) Elementary diagrams showing power, metering, relaying and control circuits.  
A detailed written step-wise explanation describing the sequence of operation shall accompany the elementary diagrams of all control and operational circuits.
  - (3) Connection diagrams.
  - (4) Interconnection diagrams. The interconnection diagrams shall show wire size and type for all interconnecting wires and cables.

3-27. Miscellaneous Provisions:

- (a) All controls shall be manually set and shall automatically maintain a preset value during steady state operation. No automatic programming is to be included.

### SECTION III

- (b) Instruments used to measure the fluid flow rates, temperatures and pressures in all the liquid metal loops plus primary heater power level shall have both manual read-out and automatic recording read-out capability. All other measurements on sump tanks, oxide control systems and air systems are to have only manual read-out capability unless otherwise specified. Inlet and outlet pressures and temperatures are to be measured from any device in the liquid metal loops which alters the state or energy level of the fluid.
- (c) Information specified in Section 1-02(c) shall, in addition to the general schematic of the system, give at least approximate values of the following at various locations in all loops for the full range of operation desired:
  - (1) Fluid temperature, pressure and flow rate.
  - (2) Dimensions
  - (3) Materials
- (d) The Contractor shall supply a system to purify commercial argon gas for use in contact with the liquid metals. The purified argon gas shall have impurities not to exceed the following:

Oxygen - 1 PPM	Hydrogen - 1 PPM
Nitrogen - 5 PPM	Water Vapor - 1 PPM
Carbon Dioxide - 2 PPM	
- (e) The Government will furnish commercial quality argon gas for the facility.
- (f) All thermocouple and low level signals shall be free of electric pickup errors.

#### 3-28. Flow Diverters:

The research requirement calls for:

- (1) flowing the test potassium vapor to either the radiant type or convective type condenser.
- (2) the change of liquid metals used as cooling fluid in the condenser coolant loop.
- (3) the isolation of the radiator for operation with the auxiliary heating loop.

This requires the provision in the system for diverting the liquid metal flow

to and from various points in the system. The Contractor shall supply flow diverters such as valves, "freeze seals", etc. to accomplish this. The flow diverter shall be designed for a positive shutoff of the inoperative portion of the system and shall accomplish the diversion of flow without cutting into any flow lines or introducing impurities into the system. The flow diverters will be operated during a period between research runs and may be either manually or remotely operated.

UNITED STATES  
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION  
LEWIS RESEARCH CENTER  
21000 BROOKPARK ROAD  
CLEVELAND 35, OHIO

May 20, 1961

EXHIBIT A

1. The following changes are hereby made in the subject specification dated April 28, 1961:

(A) Make these changes in SECTION I - DESCRIPTION, SCOPE, ETC.

(1) In Item 1-02 (b) add the following to the end "with liquid metal detector."

(2) In Item 1-02 (d) insert "Change A" after CC-841505.  
Add the following drawings

"C-841598 Compressor and Turbine Research Wing - First Floor Plan  
C-841599 Compressor and Turbine Research Wing - Second Floor Plan"

(3) In Item 1-03 (c) in the second line after "590 lb/hr" add "75 percent to 100 percent" and in the third line after the word "vapor" insert "(three separate values during 40 hour run)".

(4) In Item 1-04 (e) add the following sentence: "The liquid metals for the system shall be shipped as separate items and the system shall be shipped dry and clean of all liquid metals."

(5) In Item 1-05 (a) in the first sentence delete "120 days specified" and insert "150 calendar days".

(B) Make these changes in SECTION III - TECHNICAL PROVISIONS:

(1) In Item 3-03. add the following subparagraph (4):

"(4) Auxiliary heater loop flow rate sufficient to provide 100 degrees Fahrenheit to 400 degrees Fahrenheit temperature drops through the radiator at a 50 KW power level."

(2) In Item 3-04 (a) after "10,000 cycle operation" add "75 percent of the 10,000 hour operation will be at 1600 degrees Fahrenheit and 25 percent will be at 1800 degrees Fahrenheit."

May 20, 1961

- (3) In Item 3-04 (e) (1) delete the word "in" and substitute "which will be in".
- (4) In Item 3-04 (f) add the following to the last sentence "at maximum test fluid flow rate and at 1450 degrees Fahrenheit vapor temperature."
- (5) In Item 3-04 (h) after "line heaters with" insert "surface temperature". Also, in the last sentence of this paragraph after "250° F in" insert "not more than".
- (6) In Item 3-04 (j) in the first line delete the word "or" and substitute "or". Also, in the fourth line after the words "mass spectrometer" insert "with a qualified operator".
- (7) In Item 3-05 (a) in the sixth line delete the words "entering the test fluid boiler." and substitute "anywhere in the loop."
- (8) In Item 3-06 in the second line after the words "forced convection" insert " "shell and tube" ". In the third line after the words "outer passage" insert "(shell)". In the fourth line after the word "passages" insert "(tubes)". In the fifth line delete "1650° F" and substitute "1610° F."
- (9) In Item 3-10 (e) delete the word "outlet" in the last line.
- (10) In Item 3-12, delete the words "induction type or direct current conduction" in the second line and substitute "or direct current". Delete the fourth sentence of this paragraph in its entirety and substitute the following: "Thermocouples shall be provided for each pump with relays for indication (or enunciation) if maximum pump inlet temperature is exceeded." Add the following sentence to the end of this item: "Pressure drop in Government furnished research components will not exceed 15 PSI in the liquid and vapor passages."
- (11) In Item 3-15 delete the third line on page 3-8 and substitute the following: "have multipoint (minimum of 3) liquid level indication from 10 percent to 75 percent capacity level (excepting test)".
- (12) In Item 3-16 (a) in the first line insert "(or oil)" after the word "air". Delete (d) under 3-16 Vacuum Chamber in its entirety and substitute the following paragraph (d):
  - "(d) The Contractor shall provide all necessary jacketing, ductwork or piping and coolant supply for removing the heat absorbed by the chamber wall during all operating conditions. The temperature of the chamber inner wall shall not exceed 150° F. The temperature at any point on the wall shall not deviate from the overall average temperature by more than 25° F (based on a uniform heat absorption from the test radiator). The Contractor shall supply thermocouples to indicate the inlet

and exit coolant temperatures. The coolant exit temperature shall not exceed 150° F under all conditions. A temperature corrected flowmeter shall be provided in the coolant duct or pipe."

- (13) Correct 4-25 to "3-25" and in paragraph (a) of this item delete "Liquid Sodium Condenser" and substitute "Space Radiator and Condenser Facility".
- (14) Correct 4-26 to "3-26".
- (15) In Item 3-27 (b) in the fourth line change "and air systems" to "and air or oil systems". Add the following new paragraph "(g)":
  - "(g) The selection of any cooling oil shall provide compatibility of the oil with the alkali metals in consideration and shall be subject to approval by the Contracting Officer."

## REFERENCES

1. Anon.: Flow of Fluids. Bull. No. TT725, Tube Turns Div., Chemtron Corp.
2. McAdams, William H.: Heat Transmission. Third ed., McGraw-Hill Book Co., Inc., 1954.
3. Roark, Raymond J.: Formulas for Stress and Strain. Third ed., McGraw-Hill Book Co., Inc., 1954.
4. Weatherford, W. P., Jr.; Tyler, John C.; and Ku, P. M.: Properties of Inorganic Energy-Conversion and Heat-Transfer Fluids for Space Applications. WADD TR 61-96, Southwest Research Institute, Nov. 1961.
5. Affel, R. G.; Burger, G. H.; and Pearce, C. L.: Calibration and Testing of 2- and  $3\frac{1}{2}$ -Inch Magnetic Flowmeters for High-Temperature NaK Service. Rep. No. ORNL-2793, Oak Ridge National Labs., Mar. 4, 1960.

TABLE I. - CHEMICAL COMPOSITION OF  
HS-25 AND 316 STAINLESS STEEL

Element	Content, percent	
	HS-25	316 Stainless steel
Chromium	19.71	17.50
Nickel	10.77	13.53
Tungsten	14.75	-----
Cobalt	50.65	-----
Iron	1.95	64.00
Manganese	1.35	1.87
Molybdenum	----	2.28
Copper	----	.24
Phosphorus	.015	.015
Sulfur	.014	.023
Silicon	.70	.50
Carbon	----	.049

TABLE II. - EXTRAPOLATED VARIATION  
OF STRESS TO RUPTURE WITH  
TEMPERATURE FOR HS-25

Temperature, °F	Stress to rupture, psi
1600	10 000
1700	5 500
1800	4 200
1900	2 600



TABLE III. - STRESSES IN LIQUID-METAL PIPING

Location	Material	Temperature, °F	Pipe size, in.	Allow- able stress, $\sigma_A$ , psi	Hoop stress, $\sigma_H$ , psi	Safety factor, $\sigma_A/\sigma_H$
Heater loop:						
Hot leg	HS-25	1800	$1\frac{1}{2}$ (schedule 40)	835	437	1.91
Cold leg	HS-25	1725	$1\frac{1}{2}$ (schedule 40)	1150	527	2.18
Main heater	HS-25	1800	1 by 0.065 (tubing)	835	602	1.39
Main heater	HS-25	1900	1 by 0.065 (tubing)	520	602	.86
Vapor loop:						
Superheater	HS-25	1900	2 (schedule 40)	520	309	1.68
Vapor pipe	HS-25	1800	2 (schedule 40)	835	309	2.70
Liquid pipe	316 Stain- less steel	1400	$\frac{1}{2}$ by 0.049 (tubing)	867	103	8.42
Cooler loop:						
Hot leg	316 Stain- less steel	1600	2 (schedule 40)	277	202	1.37
Cold leg	316 Stain- less steel	1400	2 (schedule 40)	867	302	2.87

TABLE IV. - SUMMARY OF HYDRAULIC PRESSURE  
LOSSES IN TEST FACILITY

Location	Fluid	Temperature, °F	Flow velocity, ft/sec	Pressure loss, psi
Heater loop:				
Boiler to main heater	NaK	1725	16.5	6.6
Main heater	NaK	1775	17	11.9
Main heater to boiler	NaK	1800	16.5	5.7
Boiler	NaK	1750	----	6.8
Total				31.0
Vapor loop A:				
Boiler to condenser	Potassium <sup>a</sup>	1275	345	3.4
Condenser	Potassium	1300	-----	15.0
Condenser to boiler	Potassium	1400	4.7	3.4
Total				21.8
Vapor loop B:				
Boiler to radiator	Potassium <sup>a</sup>	1275	345	3.0
Radiator	Potassium	1300	-----	15.0
Radiator to boiler	Potassium	1400	4.7	4.5
Total				22.5
Cooler loop:				
Air-cooler configuration	NaK	1500	8	20.7
Radiator configuration	NaK	1500	8	21.3

<sup>a</sup>Vapor.

TABLE V. - CALCULATED TUBE LENGTHS  
FOR FOUR DISTRIBUTION CURVES FOR  
OVERALL HEAT-TRANSFER  
COEFFICIENT IN FIGURE 15

Distribution curve	NaK temperature, °F		Tube length, ft
	Inlet	Outlet	
A	1800	1725	12.2
B	1735	1660	12.5
C	1682	1607	8.6
D	1800	1725	13.3

TABLE VI. - CALCULATED BOILER  
POTASSIUM PRESSURE LOSSES  
[Flow rate, 590 lb/hr.]

Location	Pressure loss, psi
Across inlet orifices	1.35
Inlet header to tubes	0.17
12 Feet of tube	3.74
45° Bend, tube exit, and exit header	.46
Fluid momentum loss	.32
Total	6.04

TABLE VII. - CALCULATED STRESSES AND SAFETY FACTORS

## (a) Boiler shell

Boiler shell	Mean radius, R, in.	Wall thickness, h, in.	Stress, psi	Safety factor, $\sigma_A/\sigma_H$
Main cylinder	2.1	0.207	746	3.38
Sphere	4.0	.21	664	3.80
End cylinder	2.2	.21	734	3.43

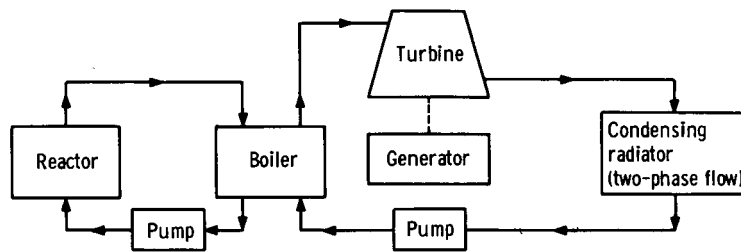
## (b) Tube sheets

Location	Temperature, °F	Sheet thickness, h, in.	Stress, psi	Safety factor, $\sigma_A/\sigma_b$
Outlet	1800	1.100	1340	3.14
Inlet	1600	.670	3290	3.04

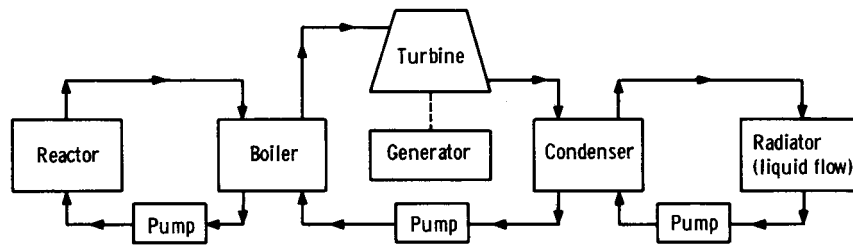
TABLE VIII. - FACILITY ELECTROMAGNETIC PUMP REQUIREMENTS

Pump unit	Design flow, gal/min	<sup>a</sup> Head rise, psi	Maximum temper- ature, °F	Duct material	Range of terminal alternating- current voltage, V
Heating loop	105	31	1725	HS-25	0 to 480
Cooling loop	105	22	1400	316 Stainless steel	0 to 480
Vapor loop	3	23	1400	316 Stainless steel	0 to 240

<sup>a</sup>From table IV.



(a) Direct-condensing system (two loops).



(b) Indirect-condensing system (three loops).

Figure 1. - Rankine cycle powerplant.

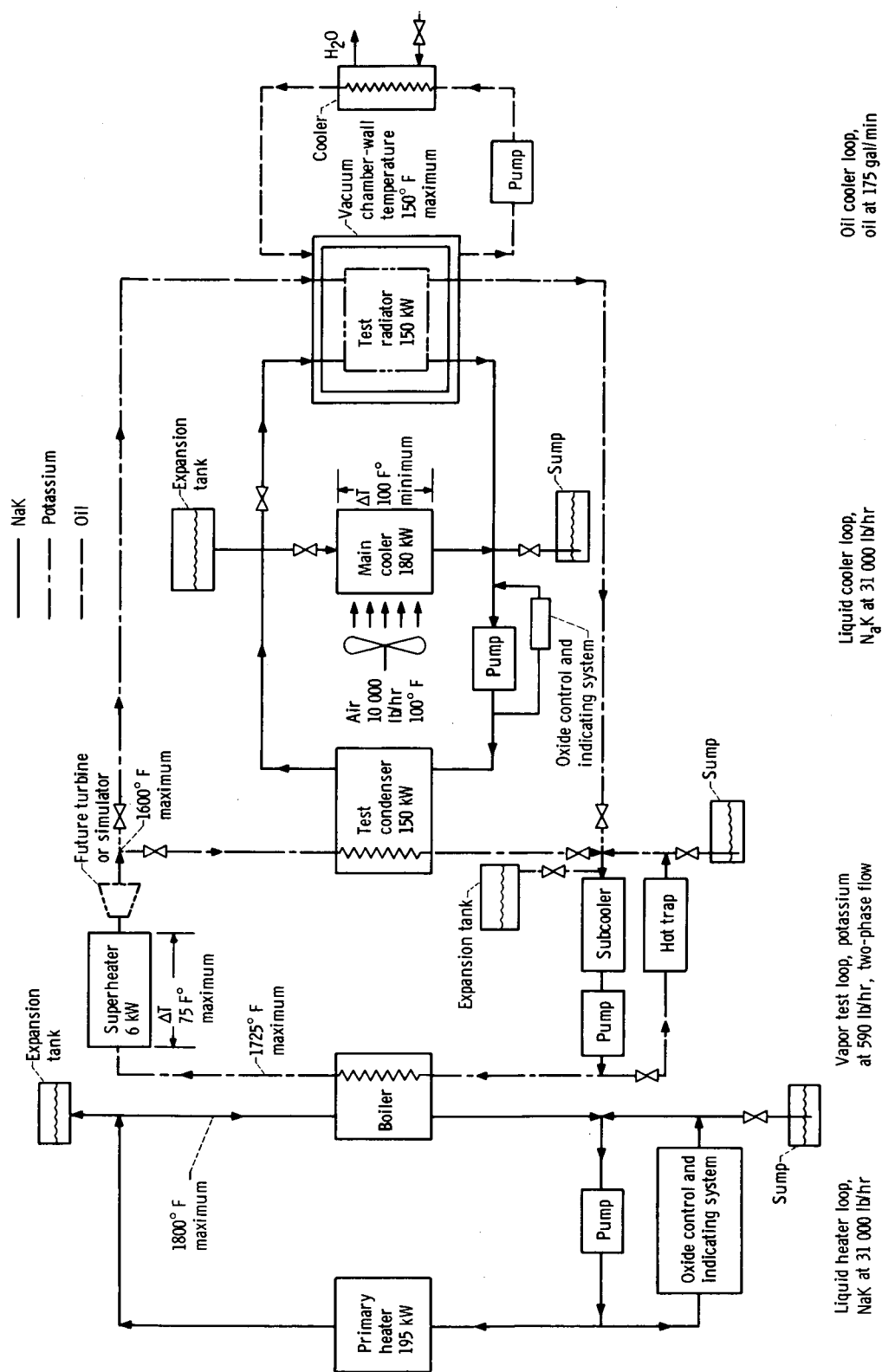
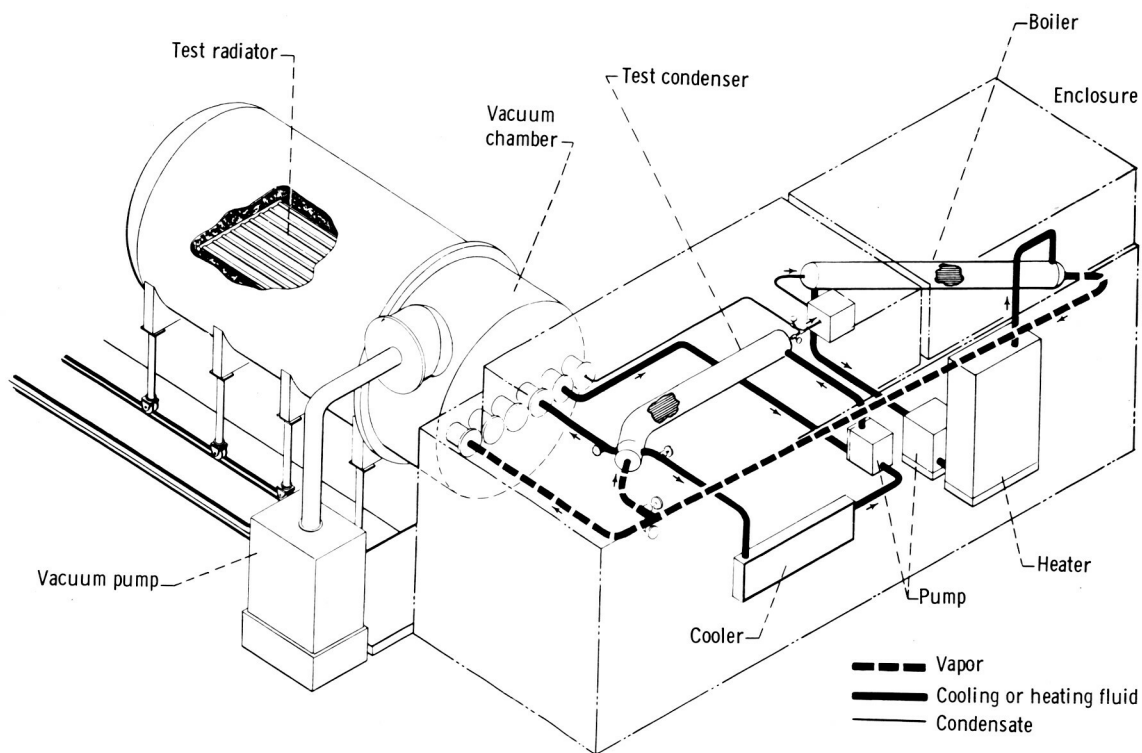
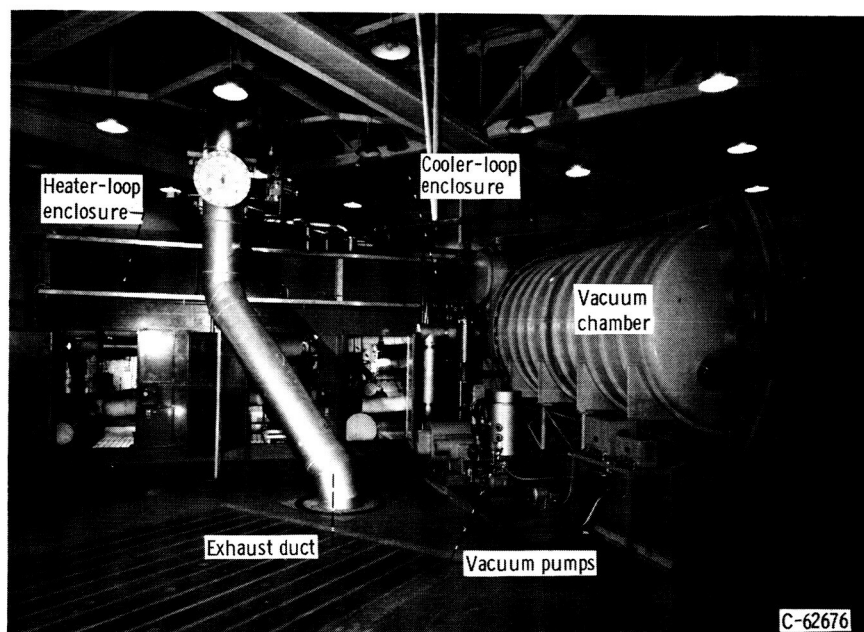


Figure 2. - Process-flow diagram of basic test facility.



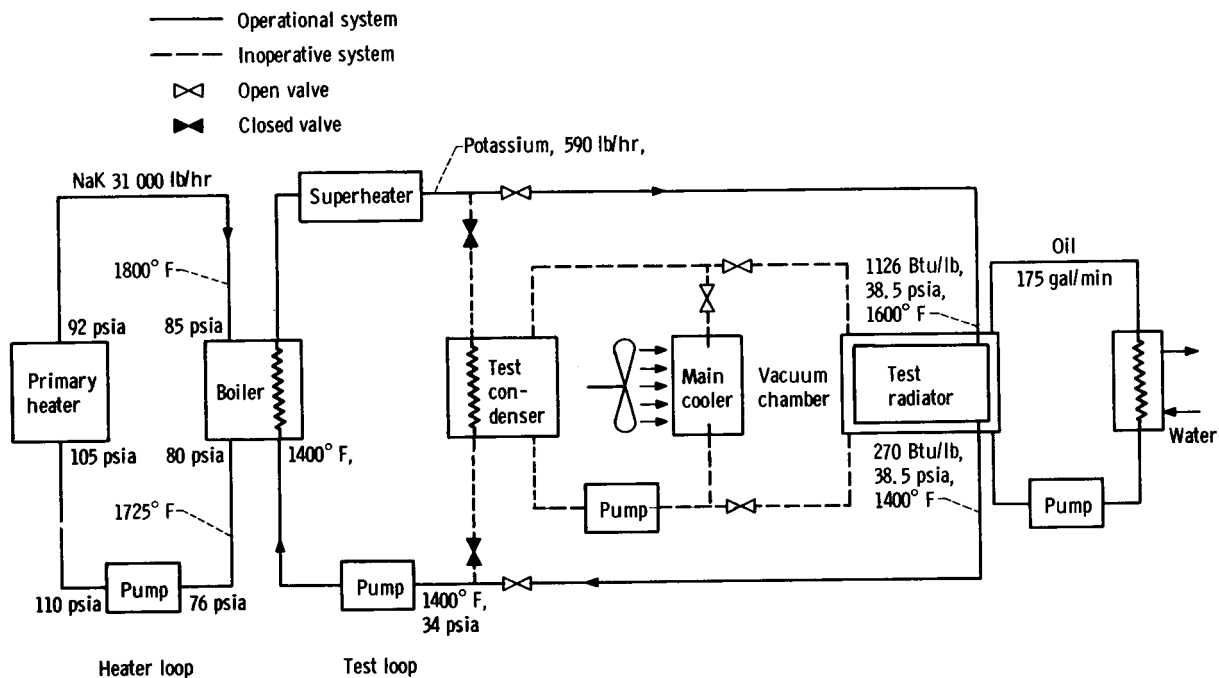
(a) Isometric drawing.

CD-8909



(b) Overall view.

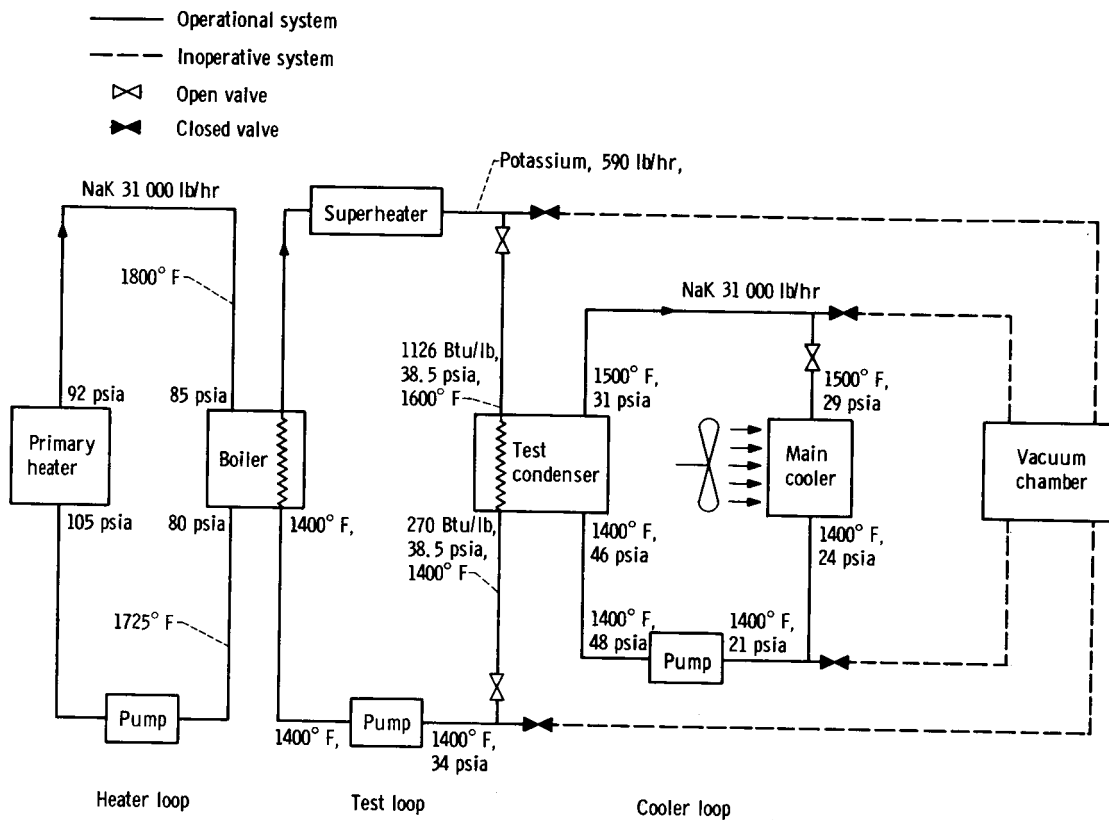
Figure 3. - Liquid-metal radiator and condenser test facility.



(a) Direct-condensing radiator test.

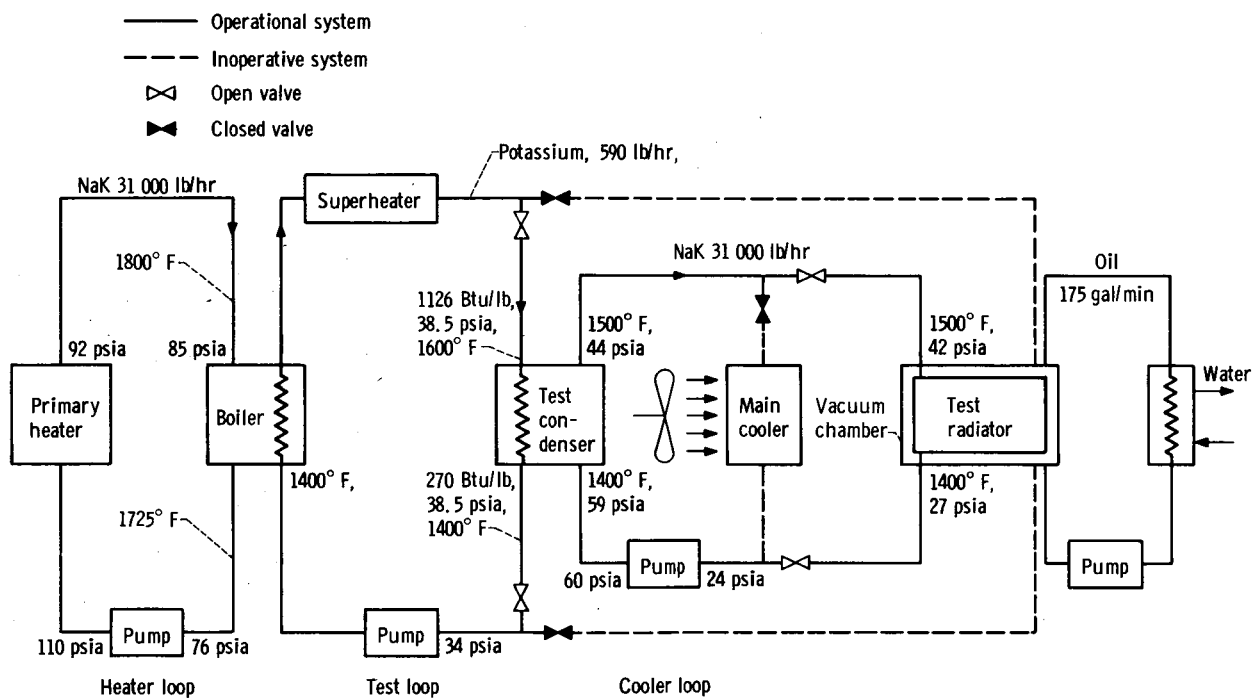
Figure 4. - Facility operating modes without turbine.





(b) Heat-exchanger condenser test.

Figure 4. - Continued.



(c) Condenser - liquid-radiator test.

Figure 4. - Concluded.

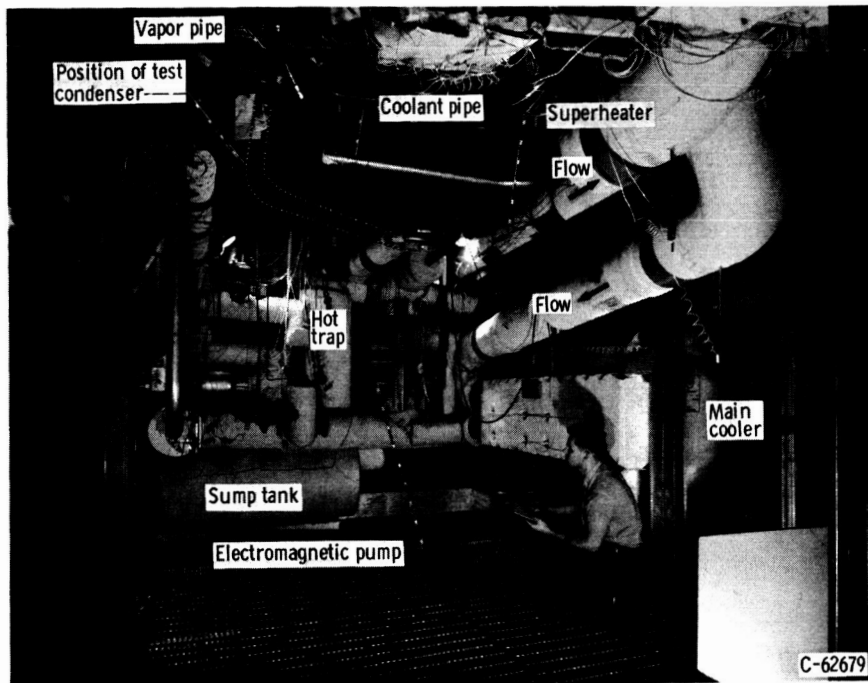


Figure 5. - Condenser-model enclosure.

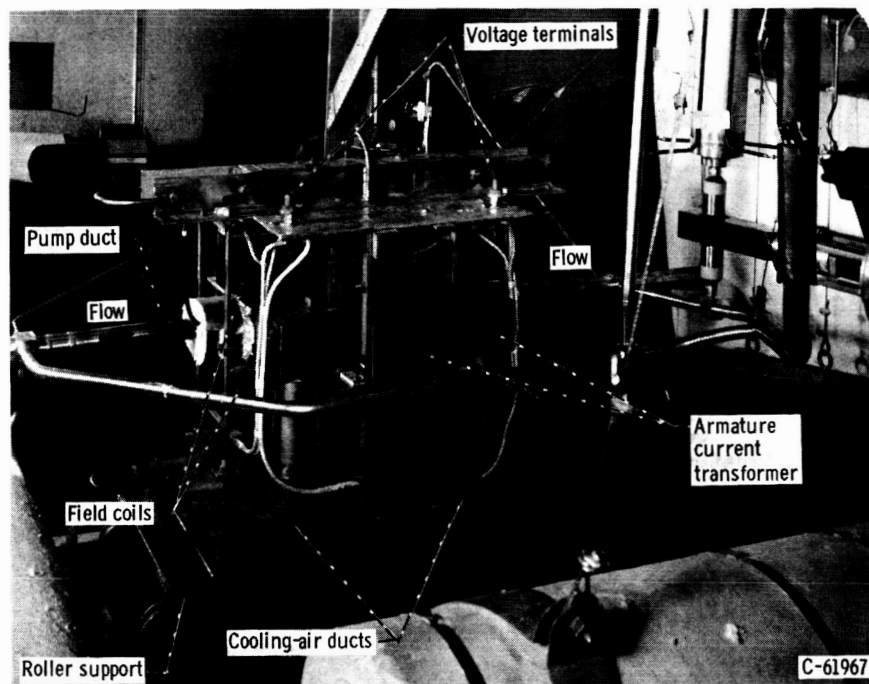
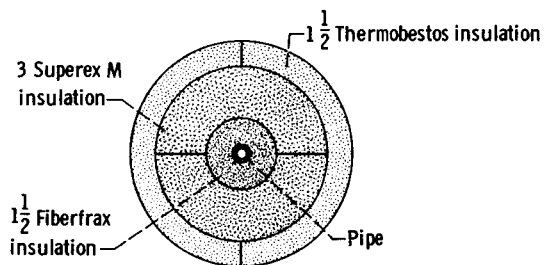
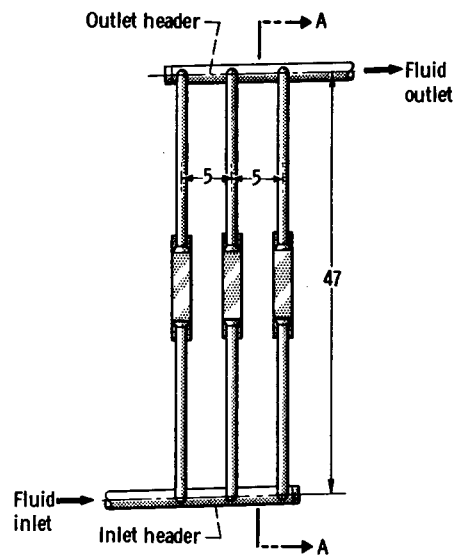
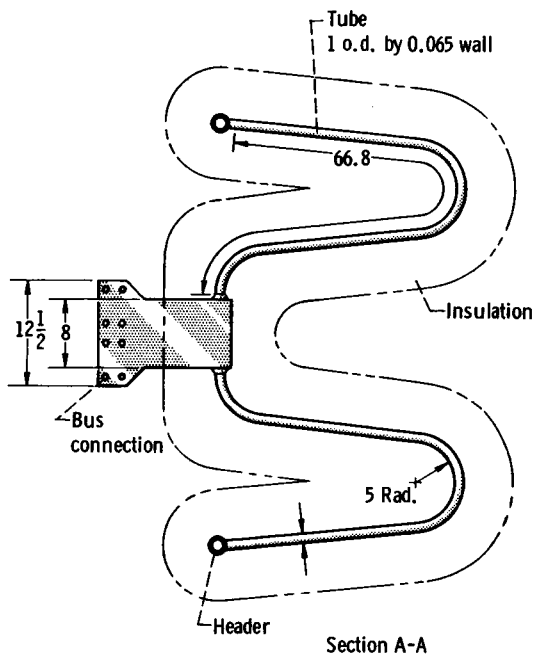


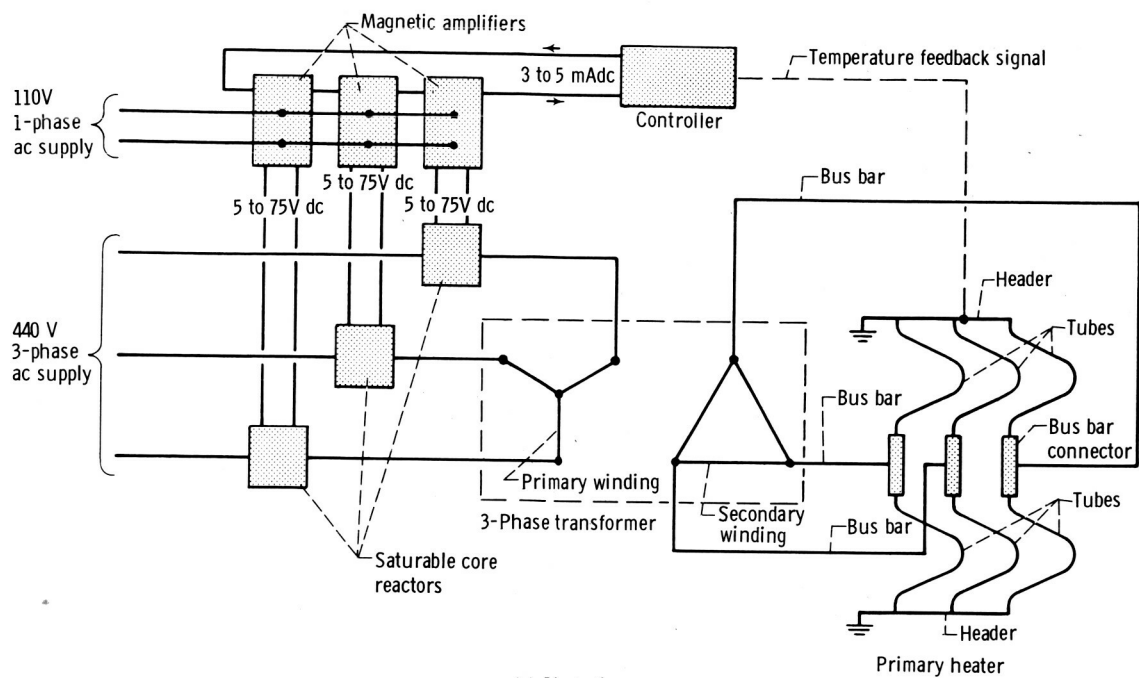
Figure 6. - Heating-loop electromagnetic pump.



Insulation detail

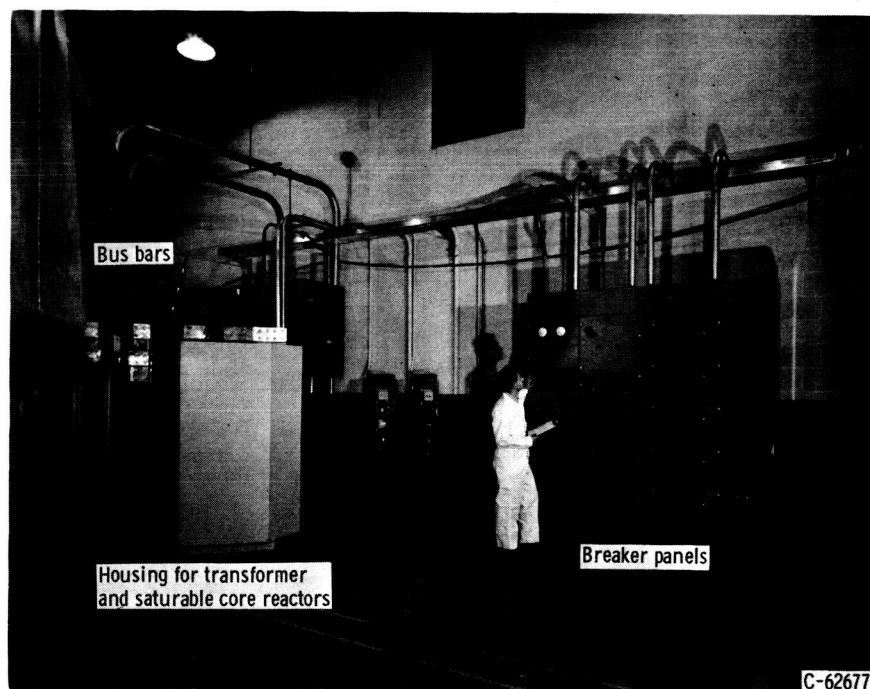
Figure 7. - Primary heater. (All dimensions are in inches.)

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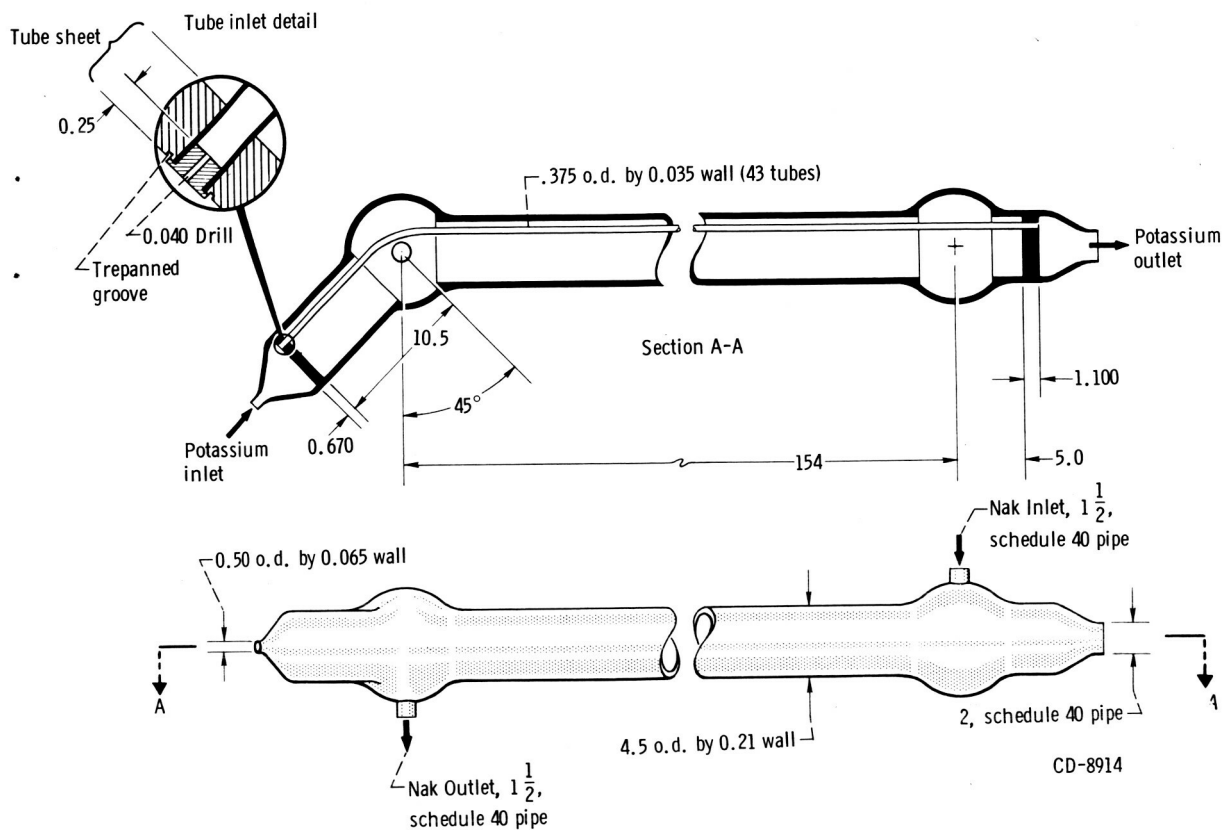
(a) Block diagram.

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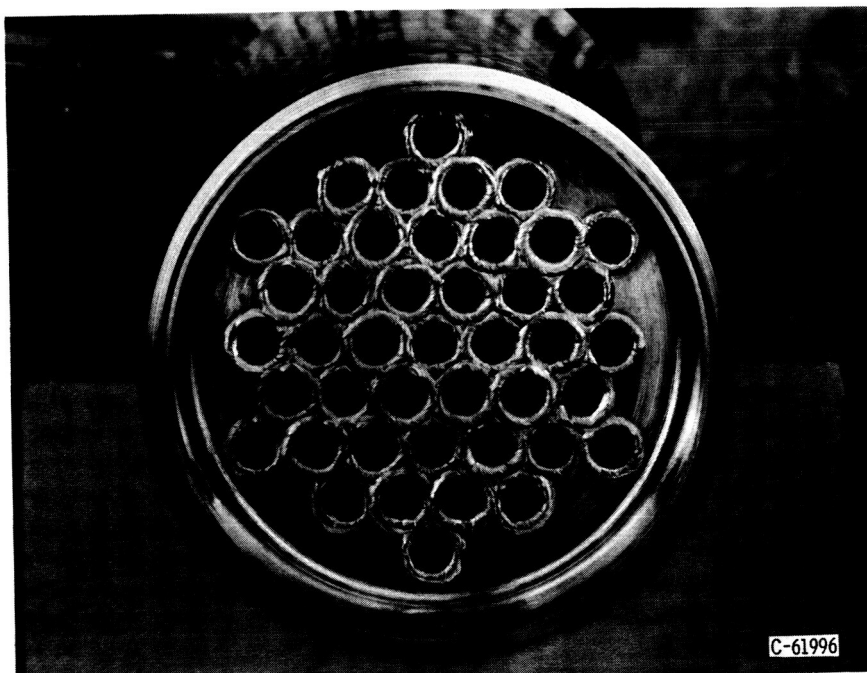


(b) Overall view.

Figure 8. - Primary heater power supply and control system.



(a) Schematic diagram.

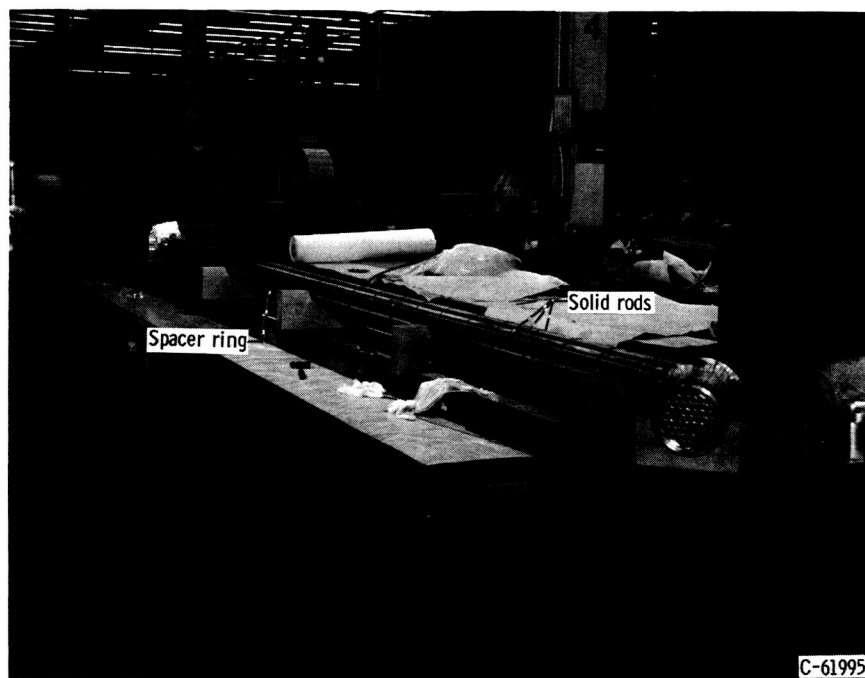


(b) Tube sheet after welding.

Figure 9. - Potassium boiler. (All dimensions are in inches.)



(c) Tube assembly with tube separators.



(d) Overall view

Figure 9. - Concluded.

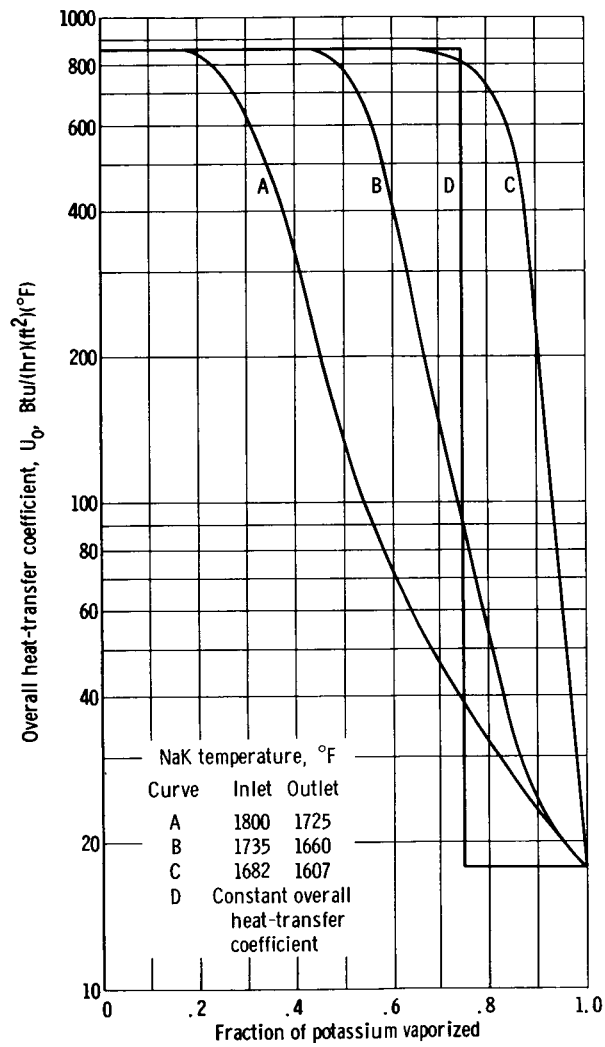


Figure 10. - Assumed distribution of overall heat-transfer coefficient in boiler tube for heating NaK. Potassium temperature, 1600° F.



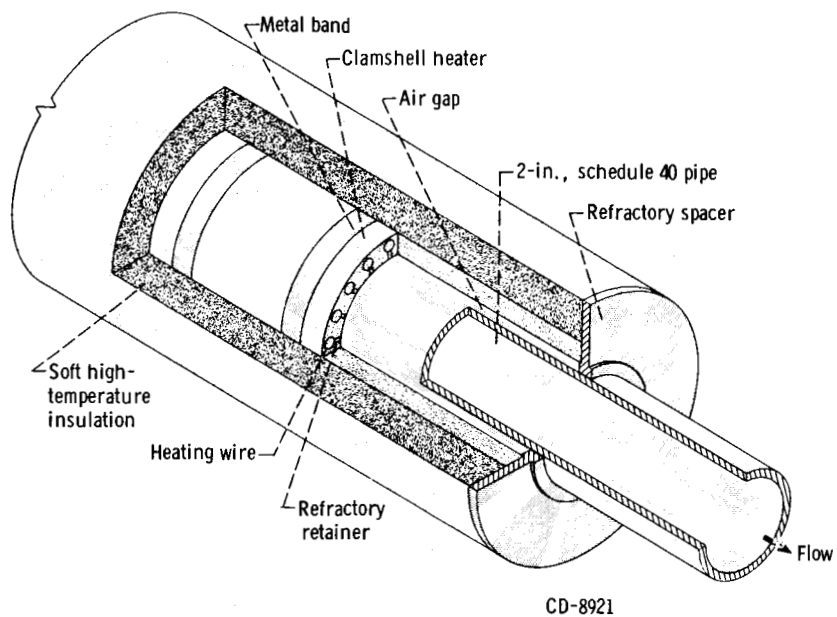


Figure 11. - Superheater construction.

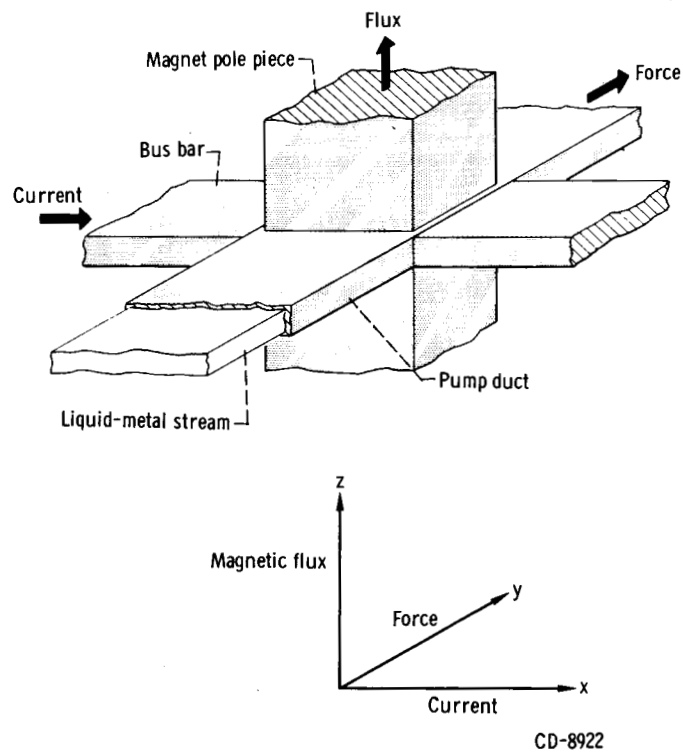


Figure 12. - Schematic diagram of electromagnetic conduction pump.

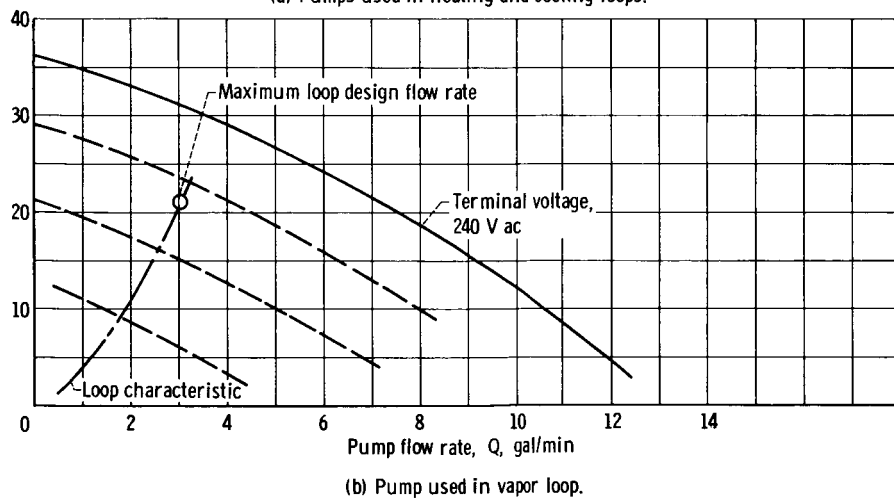
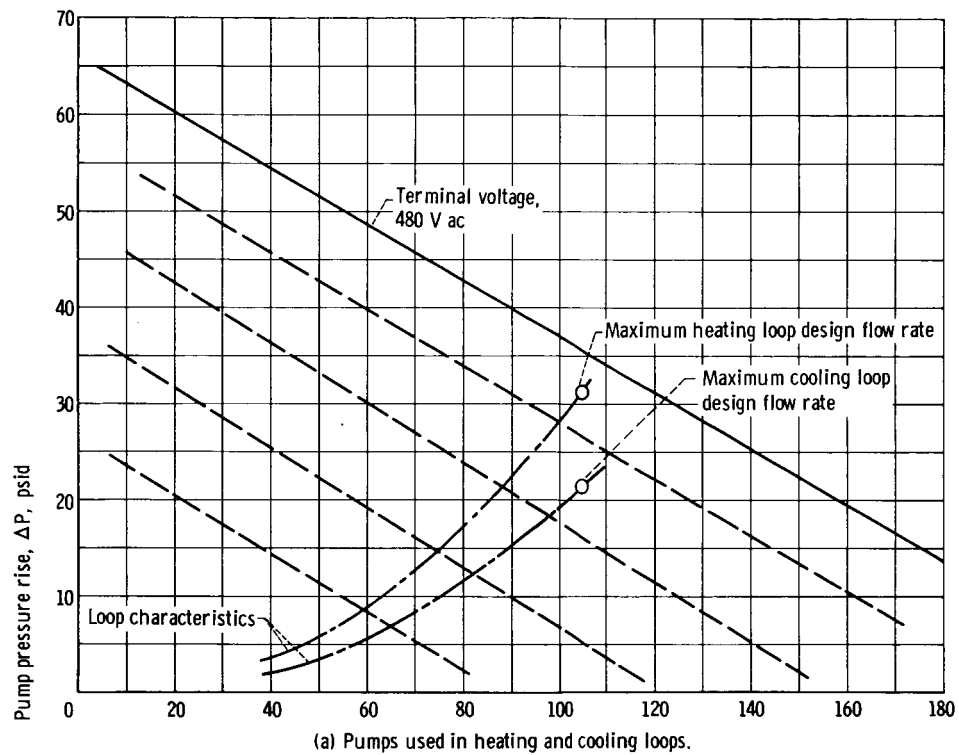
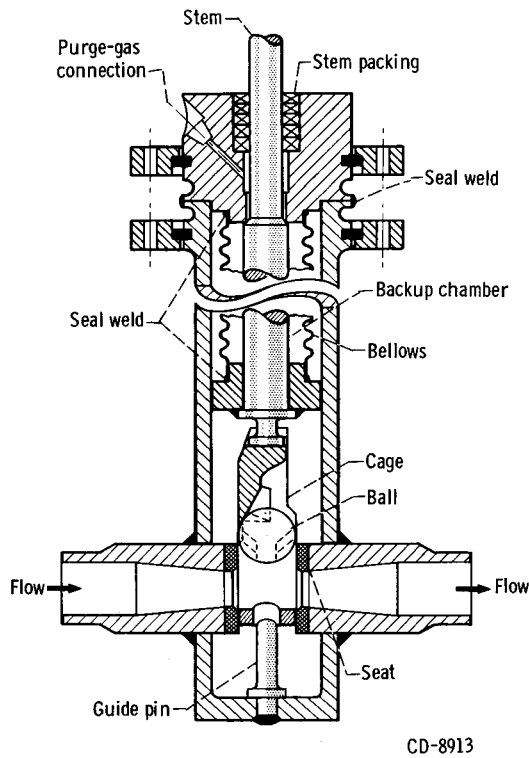
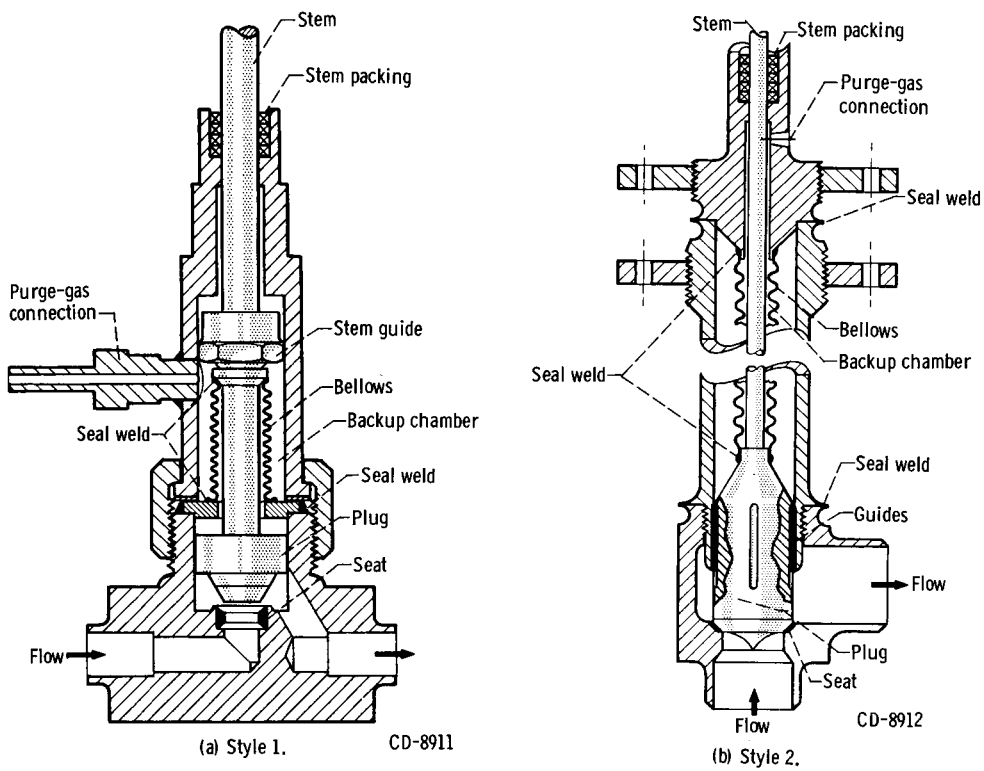


Figure 13. - Liquid-metal pump performance.



(c) Style 3.

Figure 14. - Liquid-metal valves.

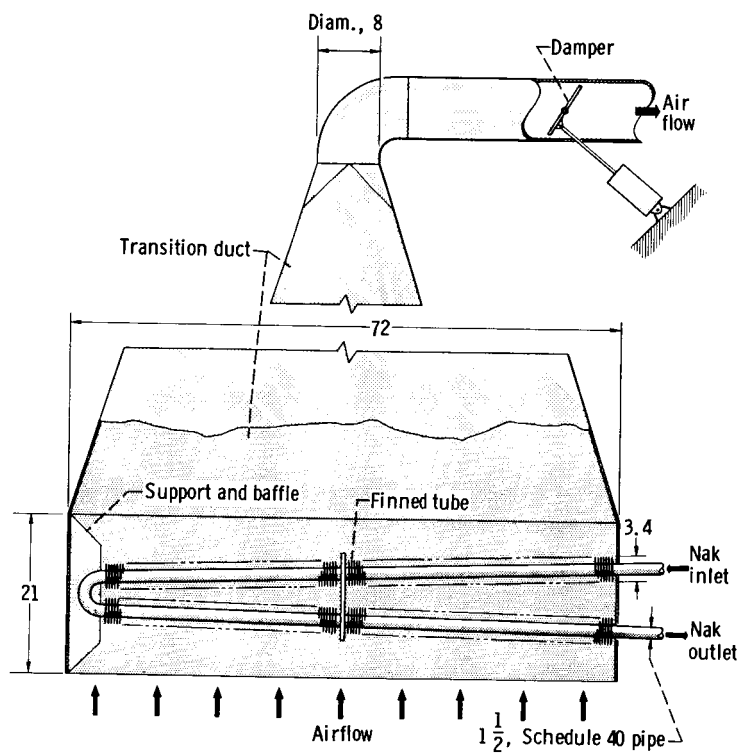
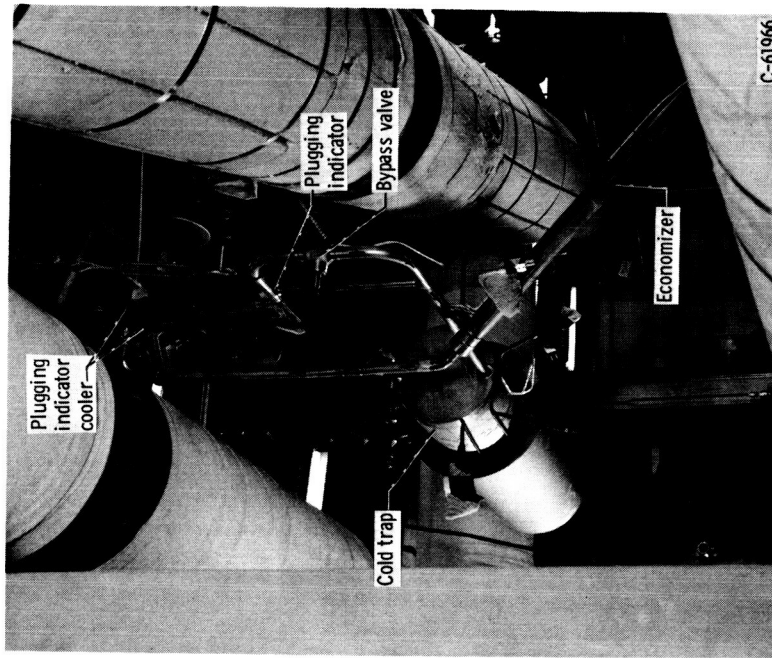
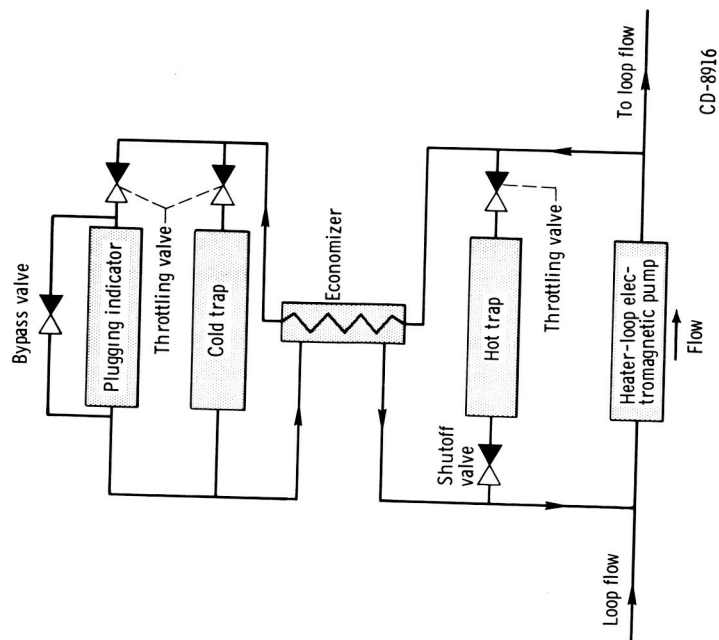


Figure 15. - Side view of air cooler for Nak coolant. (All dimensions are in inches.)



(b) Overall view.



(a) Block diagram.

Figure 16. - Heater-loop oxide control and indicating system. (Flow direction shown by arrows.)

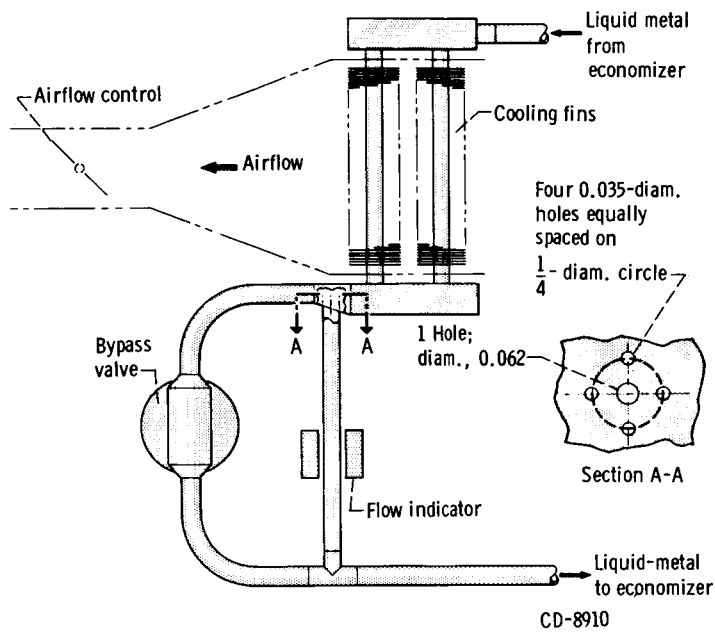


Figure 17. - Plugging indicator. (All dimensions are in inches.)

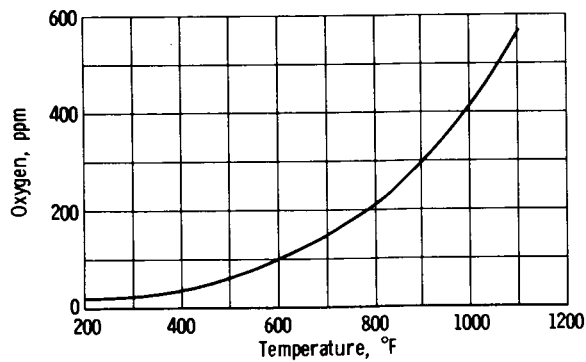


Figure 18. - Solubility of sodium oxide and sodium hydroxide in NaK-78.

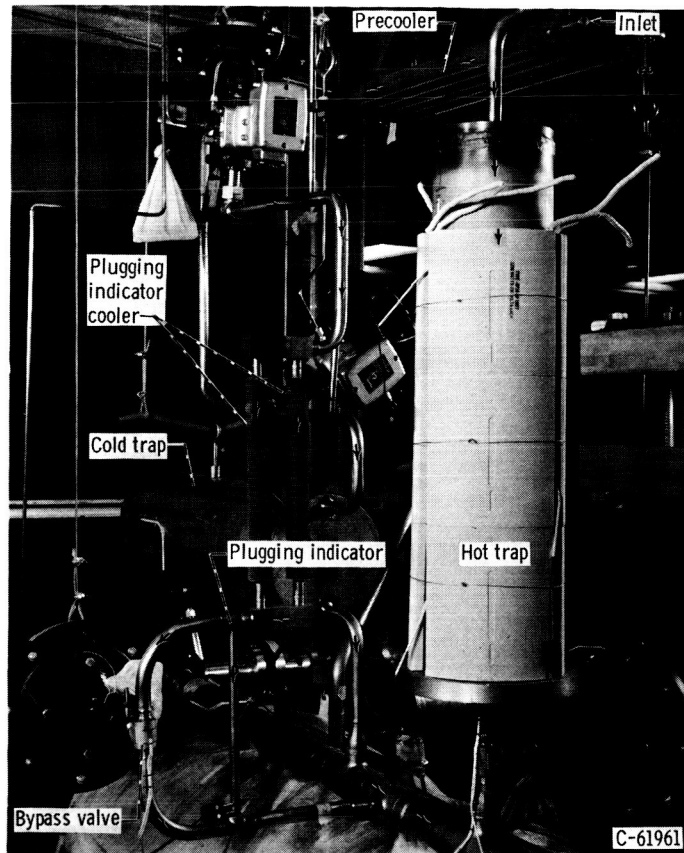


Figure 19. - Oxide control and indicating system for cooling loop.  
(Flow direction shown by arrows.)

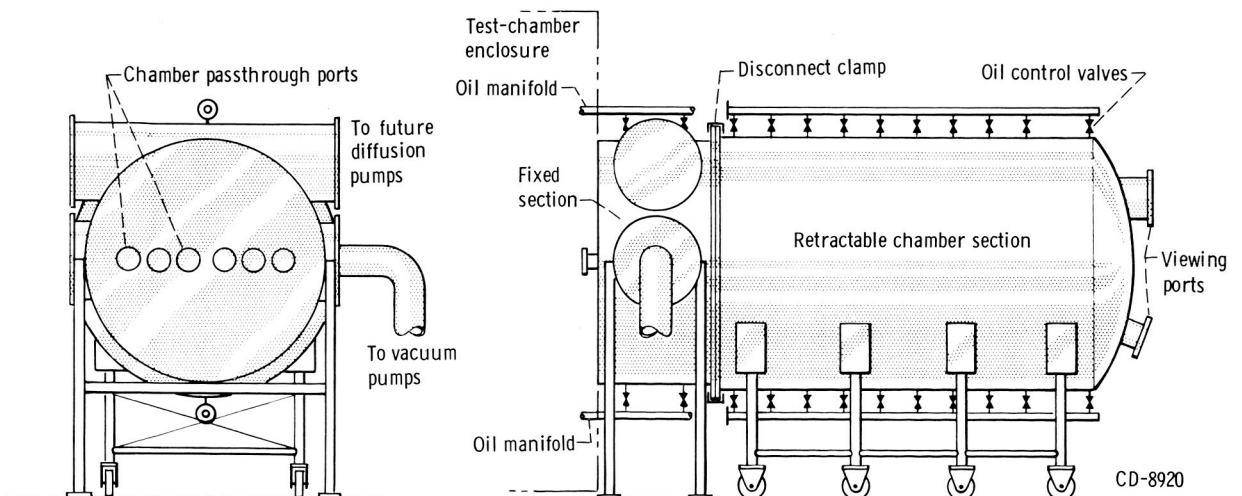


Figure 20. - Vacuum chamber.

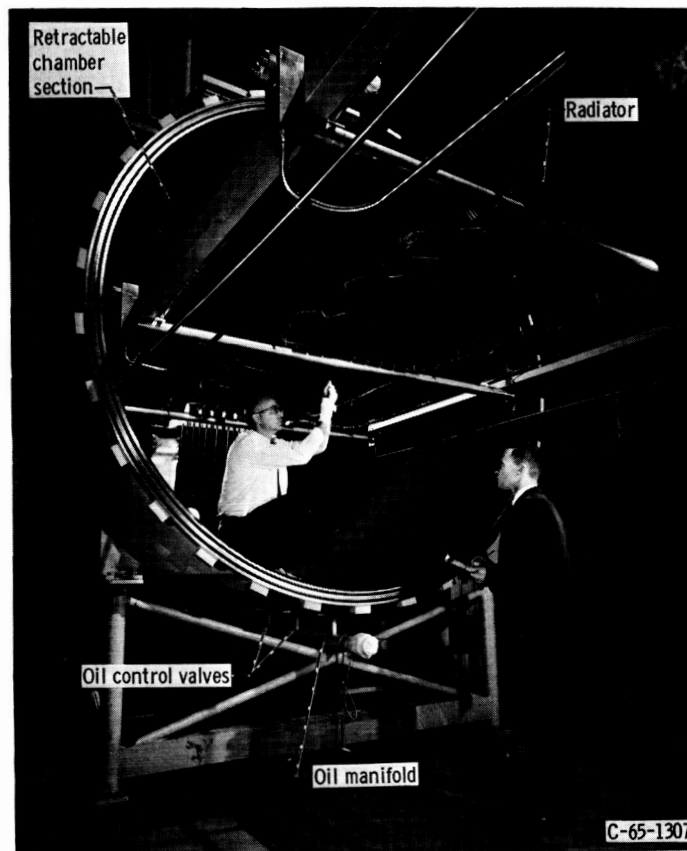


Figure 21. - Model radiator in vacuum chamber.

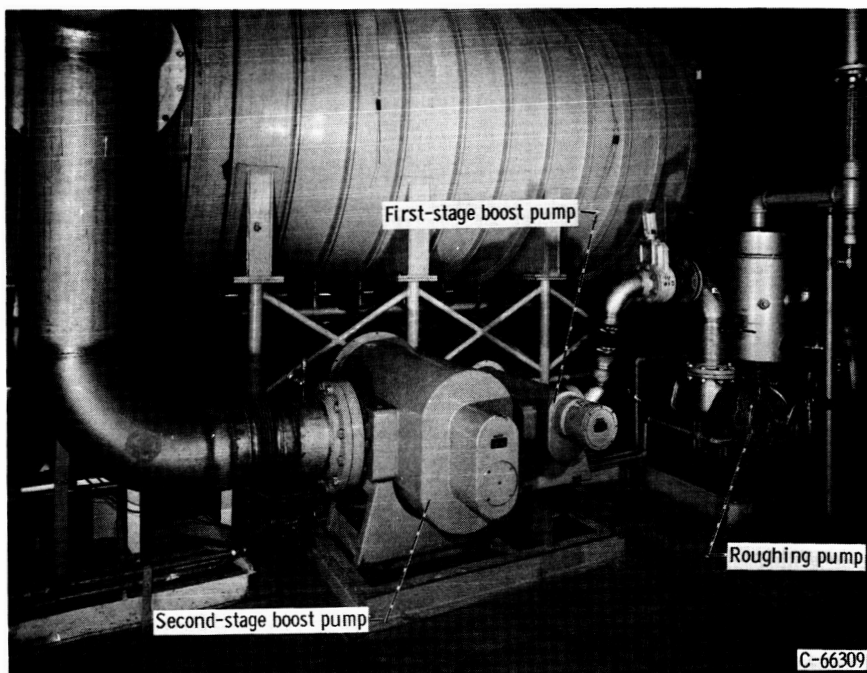


Figure 22. - Vacuum-chamber pumping system.



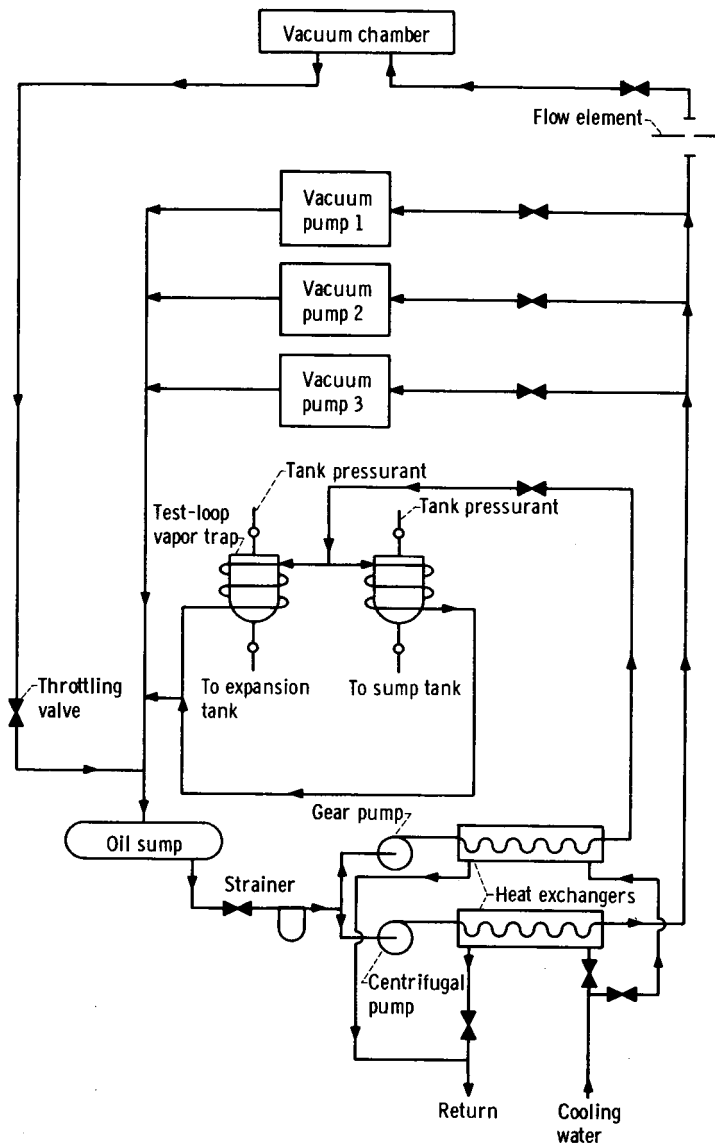


Figure 23. - Oil-cooling system for vacuum chamber.

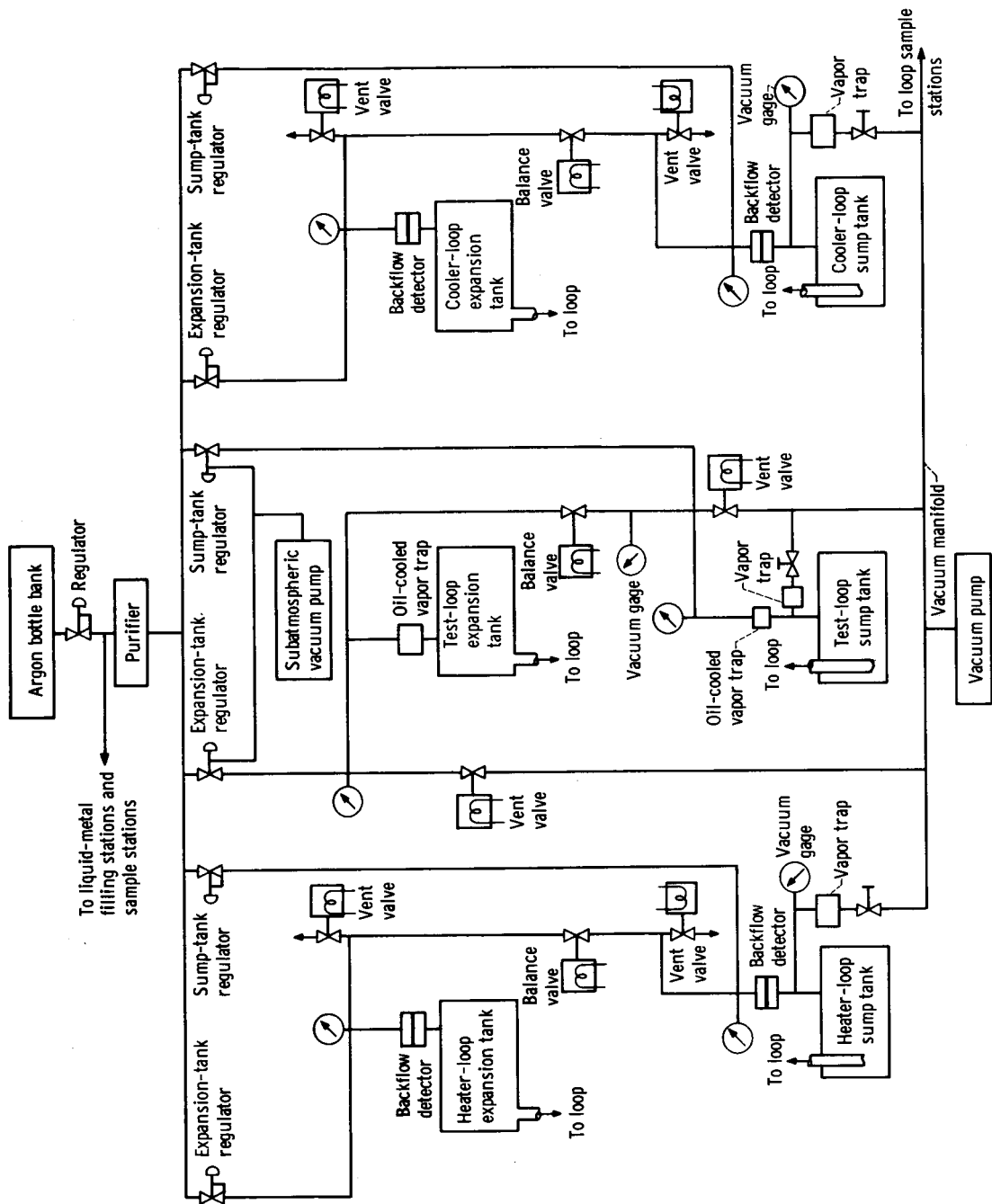


Figure 24. - Argon pressurization and vacuum purging system.

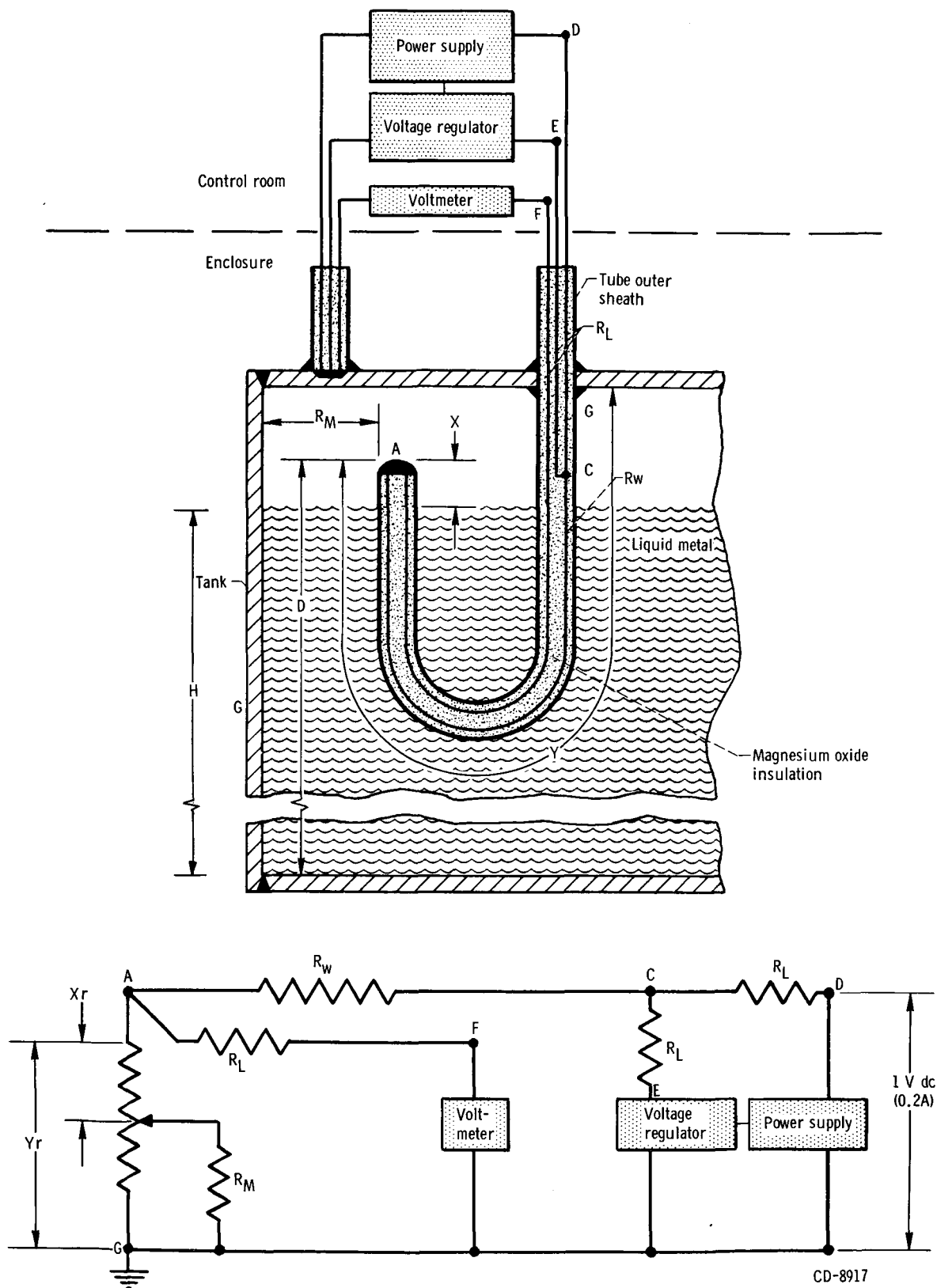


Figure 25. - Liquid-level sensing unit and circuit diagram. Lead resistance,  $R_L$ , 2 to 4 ohms; resistance of liquid metal and container,  $R_M$ , 0.0; resistance of lead from A to C,  $R_W$ , 2 ohms; resistance per unit length,  $r$ , approximately  $5 \times 10^{-5}$  ohm per inch.

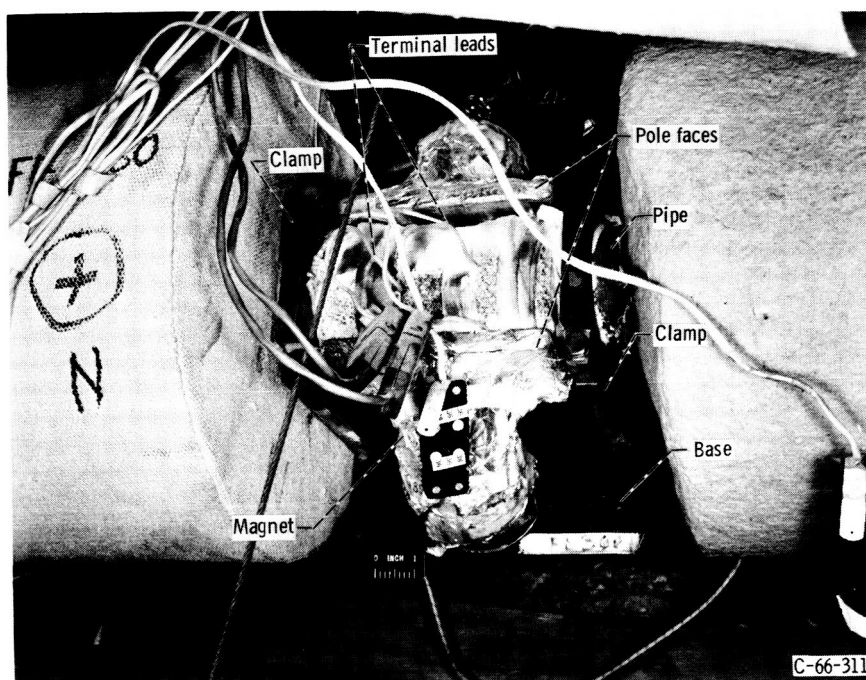


Figure 26. - Installed electromagnetic flowmeter.

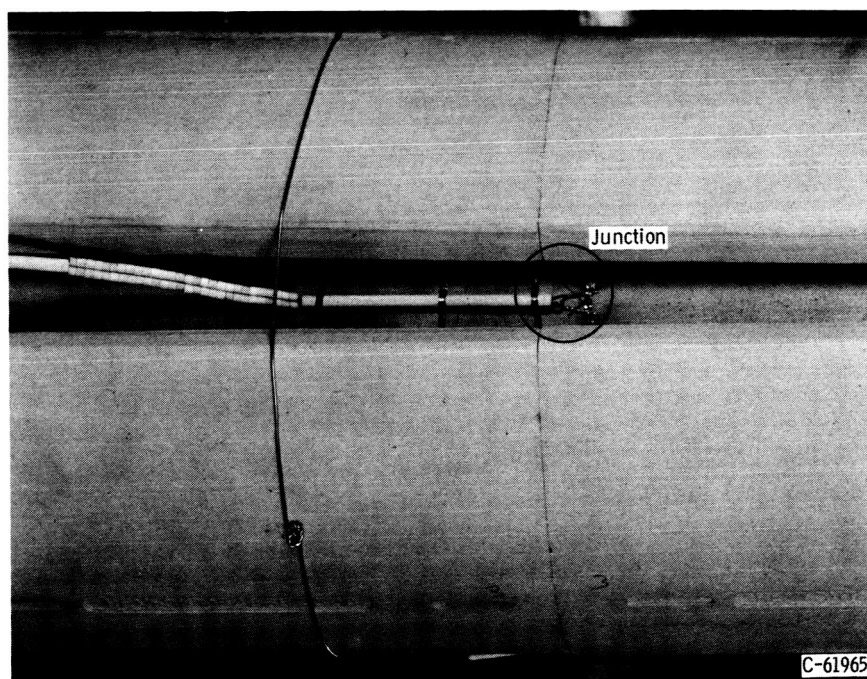


Figure 27. - Typical open-junction thermocouple.

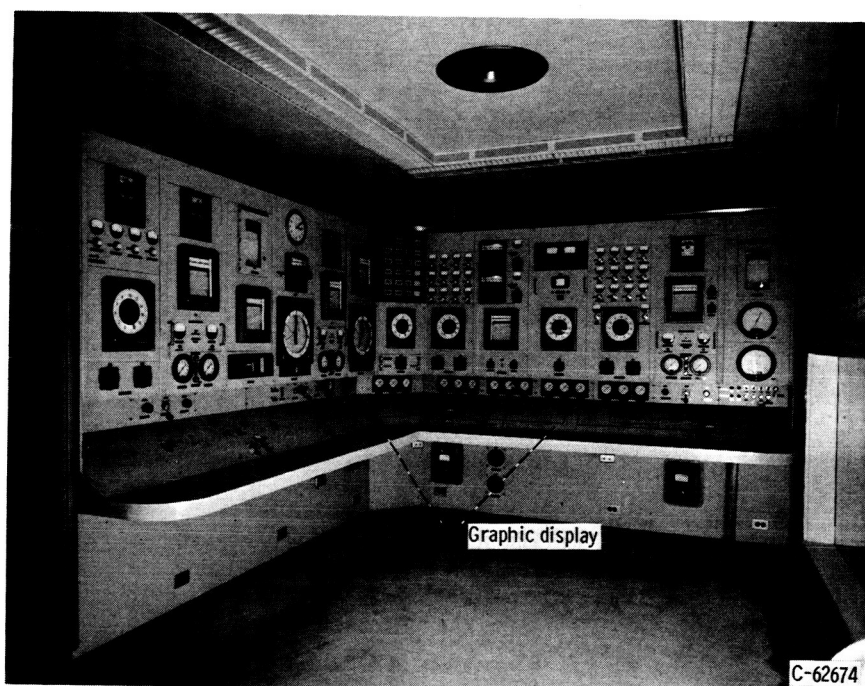


Figure 28. - Test facility control panel in remote control room.